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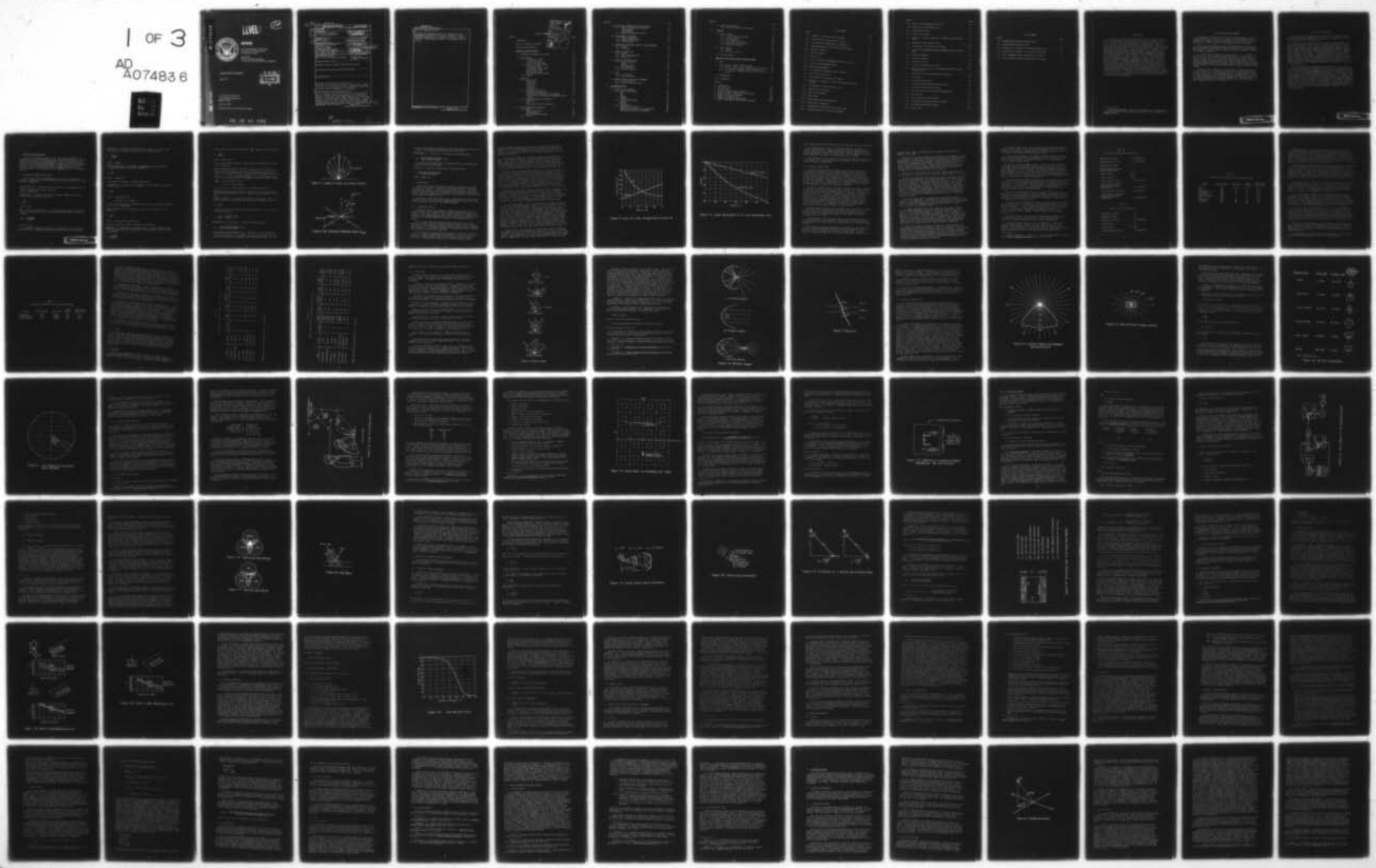

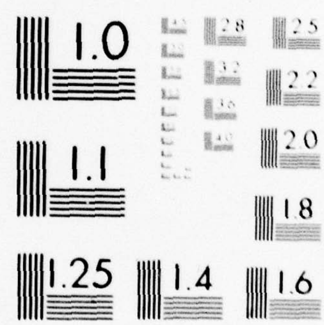

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LIGHTING DESIGN HANDBOOK

August 1979

An Investigation Conducted by
LUM-I-NEERING ASSOCIATES
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With the advent of increasingly more efficient light sources, interior lighting levels have continued to rise dramatically. However, in many cases these higher lighting levels caused more complaints than the previously lower lighting levels. This was because many of the lighting engineers who designed the newer lighting layouts ignored, or were ignorant of, many parameters

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that need to be considered other than illumination levels. A knowledgeable background of lighting fundamentals includes a thorough understanding of such topics as equivalent sphere illumination, visual comfort probability, daylighting, and controls.

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INTRODUCTION

For many years, numerous lighting experts were convinced that optimum visibility occurred at lighting intensities near those normally found outdoors. With the advent of increasingly more efficient light sources, interior lighting levels have continued to rise dramatically. However, in many cases these higher lighting levels caused more complaints than the previous lower lighting levels. This was because many of the lighting engineers who designed the newer lighting layouts ignored, or were ignorant of, the many parameters that need to be considered other than footcandle levels. Achieving a knowledgeable background in lighting fundamentals includes a thorough understanding of these parameters. This *Lighting Design Handbook* is an educational tool to help you achieve this goal. When supplemented with the *IES Lighting Handbook*, 5th Edition†, you will be able to gain a valuable knowledge of lighting fundamentals and applications. This knowledge is the key to sound engineering judgment in solving the problems of specifying and designing lighting systems that provide improved visibility and better energy conservation than those systems determined by classical uniform lighting methods. Design and application techniques based on an inadequate and shaky foundation in lighting fundamentals may result in poor visibility and in false savings that can produce increased energy consumption over the long run. Your challenge is to learn that both energy savings and better visibility can indeed be realized through the proper application of thorough lighting fundamentals.

---

†*IES Lighting Handbook*, 5th Edition, available from the Illuminating Engineering Society, 345 East 47th St., New York, NY 10017. Members $30.00, nonmembers $37.50.

HOW IS THE HANDBOOK ORGANIZED?

The handbook is divided into four sections plus an appendix. Section 1 contains the important concepts for a complete understanding of artificial lighting and its impact on energy conservation. The user should thoroughly study Section 1 before moving on to the remaining parts of the manual.

Section 2 helps the user understand the complex nature of daylighting. Without a complete understanding of the interactions affecting daylighting, the engineer will not be properly equipped to evaluate the impact of daylighting on energy conservation.

The key to energy conservation is system control. It is important to account not only for the amount of power used, but also for the length of time it is used. Section 3 discusses the types of controls that can be utilized in a lighting system, while Section 4 examines the impact on energy savings by properly integrating the two sources of light (artificial lighting and natural daylighting) with an automatic control system. Without a properly designed automatic control system, energy savings utilizing daylight are questionable.

The Appendix gives examples of the application of fundamental techniques discussed in the text. The authors caution the user against skipping over the body of the text to get to the applications. The major cause of errors in lighting applications and the resulting waste of energy is due to the lack of indepth understanding of the complex interaction of lighting design. If your goal is sensible, sound energy conservation policy, the user must thoroughly understand Sections 1, 2, 3, and 4.

HOW TO USE THE HANDBOOK

The authors cannot overemphasize the importance of a thorough understanding of lighting fundamentals. The purpose of the handbook is to help in achieving this needed understanding.

Some of you may be thinking, "I have been doing lighting design for 10 years - who needs this?" Ask yourself: Is watts per square foot or zonal cavity really lighting design? Do your lighting designs conserve energy? Do you really understand the technical data necessary to evaluate lighting design? What is VCP and ESI? Which source has a higher efficacy - fluorescent or mercury vapor? What is a Lambertian Surface - what is its significance? Why does an object take on a different appearance under different lighting systems? What happens to performance when you arbitrarily remove lamps? These are all essential questions that must be understood if you are to be a competent designer. Your design decisions will determine the effectiveness of your energy conservation decision. The key to your success is hard work and study. This handbook should make your task easier - use it and do a professional job.

The authors suggest you rapidly read through Sections 1, 2, 3, and 4. The first time through skip the Appendix. After the first reading of the body of the text, go back to the beginning. Slowly read and study Section 1 again. Have a copy of the *IES Lighting Handbook* (5th Edition) available so that references to it can be studied as one goes through Section 1. Once Section 1 has been thoroughly studied, the user should move on to Section 2. Indepth reading and studying of Section 2 should follow the same technique used for Section 1. Sections 3 and 4 should be studied in a like manner once an indepth understanding of Section 2 has been gained. Ask yourself, do I really have a complete grasp? If the answer is NO, don't feel discouraged. Going back over the four sections three or four times will help to set the concepts more clearly in your mind. Once you have a thorough understanding of Sections 1 thru 4, move on to the Appendix.

I. ARTIFICIAL LIGHTING DESIGN

This section presents information, data, and concepts essential to the understanding of artificial lighting design. Important fundamental concepts of lighting are essential to the understanding of both design and analysis of lighting. The interrelationships between the luminous, thermal, and acoustical environments are discussed as they relate to lighting design and energy conservation. Energy consideration, design techniques, and cost along with factors essential to the application of the fundamental principles conclude the section.

1.1 PHOTOMETRIC TERMINOLOGY AND UNITS

A more complete set of definitions may be found in the *IES Lighting Handbook*[1]. Presented here are the definitions of the basic quantities of light and their relationships.

LUMINOUS ENERGY (Q_v): Energy traveling in the form of electromagnetic waves to which the human visual system is sensitive.
UNITS: lumen-seconds

LUMINOUS FLUX (ϕ): The time rate of flow of luminous energy (Q_v) emitted, transferred, or received by a surface.

$$\phi = \frac{dQ_v}{dt}$$

UNITS: lumen

LUMEN: The unit of luminous flux. It is the flux emitted within a unit solid angle (1 steradian) by a point source having a uniform luminous intensity of 1 candela.

$$\text{LUMEN} = \frac{1\ \text{candela}}{\text{steradian}}$$

---

[1] *IES Lighting Handbook*, 5th Edition, J. E. Kaufman and J. F. Christensen, Editors, New York: Illuminating Engineering Society of North America, 1972.

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STERADIAN (ω): A geometric relation which is the ratio of the sphere area enclosed by a solid angle to the radius of the sphere squared.

$$\omega = \frac{A_{sphere}}{r^2}$$

UNITS: radians

LUMINOUS EXITANCE (M): The luminous flux emitted by a very small surface divided by the area of that surface element.

$$M = \frac{d\phi}{dA}$$

UNITS: lumens/meter^2

Also known as the Density of Luminous Flux emitted.

ILLUMINANCE(E): The luminous flux incident on a small surface per unit area of that surface.

$$E = \frac{d\phi}{dA}$$

UNITS: lumens/meter^2 (lux)

lumens/meter^2 (footcandle)

Also known as the Density of Luminous Flux incident on a surface and commonly referred to as Illumination.

LUMINOUS INTENSITY (I): The luminous flux per unit solid angle in a given direction.

$$I = \frac{d\phi}{d\omega}$$

UNITS: lumens/steradian = candela (cd)

Luminous intensity is commonly referred to as candlepower.

LUMINANCE (L): The luminous flux leaving a point in a given direction (θ) per unit of projected area of that point per unit solid angle in which the flux is contained.

$$L = \frac{d^2\phi}{d\omega dA\cos\theta}$$

Since luminous intensity is defined as $I = \frac{d\phi}{d\omega}$, luminance is also defined as

$$L = \frac{dI}{dA\cos\theta}$$

UNITS: candela/meter^2

In the United States luminance is usually given in footLamberts (fL) where $1\ fL = 3.426\ cd/m^2$.

SPECTRAL LUMINOUS EFFICIENCY: The ratio of radiant flux at wavelength λ_m to that at any other wavelength such that both wavelengths produce equally intense visual sensations and λ_m is chosen so that the maximum value of this ratio is 1. The Spectral Luminous Efficiency of all wavelengths defines a function that is the response of the human visual system to radiant energy.

Symbol: $V(\lambda)$ for photopic vision

$V'(\lambda)$ for scotopic vision

The function $V(\lambda)$ is commonly known as the Standard Observer Curve.

LAMBERTIAN SURFACE (Perfect Diffuser): A surface that absorbs all incident radiant energy and reradiates all that energy according to Lambert's Cosine Law.

LAMBERT's COSINE LAW: States that the intensity at any angle is equal to the intensity normal to the surface times the cosine of the angle - Fig. 1-1.

$$I_\theta = I_N\cos\theta$$

A Lambertian surface will maintain constant luminance, L, no matter what the viewing angle because

$$L = \frac{dI_\theta}{dA\cos\theta} = \frac{d(I_N\cos\theta)}{dA\cos\theta} = \frac{I_N}{A}$$

REFLECTANCE (ρ): The ability of a surface to reradiate energy.

$$\rho(\%) = \frac{\text{total reflected energy}}{\text{total incident energy}} \times 100\%$$

BI-DIRECTIONAL REFLECTION FACTOR ($\beta_{\theta,\psi}$): The ratio of incident radiation to the reflected radiation for an observer at a fixed viewing angle for each position of the source in a hemisphere above the surface - Fig. 1-2. This

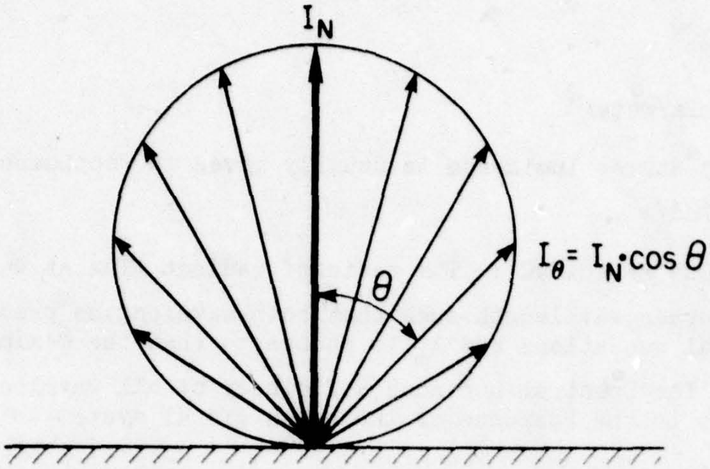

Figure 1-1 Lambert's Cosine Law (Perfect Diffuser)

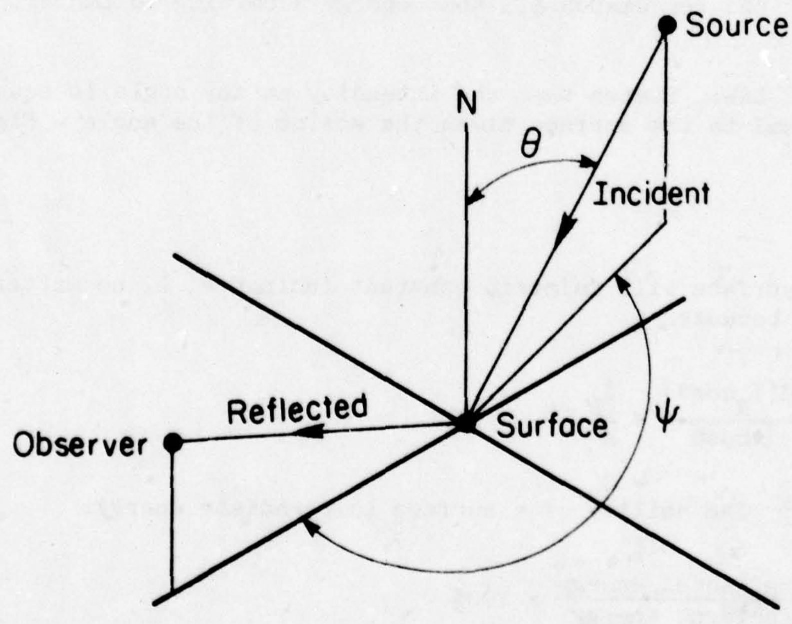

Figure 1-2 Bi-Directional Reflection Factor $\beta_{(\theta,\psi)}$

has not been accepted as nomenclature by the IES (Illuminating Engineering Society). Also known as the luminance factor indicatrix.

TRANSMITTANCE (τ): The ability of a surface to pass radiant energy.

$$\tau(\%) = \frac{\text{total transmitted energy}}{\text{total incident energy}} \times 100\%$$

It is believed that indicatrixes of transmittance will be needed with more sophisticated design techniques.

EFFICACY (ξ): The ratio of light output to electrical input.

$$\xi = \frac{\text{total luminous flux emitted}}{\text{total input power}}$$

UNITS: lumens/watt

1.2 LIGHT SOURCES

Light sources (lamps) used today in artificial lighting can be divided into two main categories - incandescent and gaseous discharge. The gaseous discharge type of lamp is either low pressure or high pressure. Low pressure gaseous discharge sources are the fluorescent and low pressure sodium lamps. Mercury vapor, metal halide, and high pressure sodium lamps are considered high pressure gaseous discharge sources.

Besides the sources above, which are the common lamps used for lighting, a number of exotic sources have been designed for special applications. These exotic sources are found in the *IES Lighting Handbook*[1].

1.2.1 Incandescent Sources

Incandescent Lamps. The incandescent lamp produces light by passing current through a wire (filament), and is the most commonly used source even though it is the least efficient. These lamps are available in numerous sizes, wattages, bulb configurations, filament styles, and base types. These can be found in the *IES Lighting Handbook*[1], Section 8 or any lamp manufacturer's catalog.

One of the most important characteristics of any light source is its ability to convert electrical energy into luminous energy. This is known as lamp efficacy. The incandescent lamp has efficacies ranging from 4 lumens/watt to 24 lumens/watt. For comparison purposes the incandescent lamp is typically said to have an efficacy of 20 lumens/watt.

Cost of light not only depends on the efficacy of the source but also on its life. Incandescent lamps have an average life of 1,000 hours or about 5 months for a typical burning period of 8 hours/day (52 wk/yr x 6 days/wk x 8 hr/day = 2,496 hours/yr). Lamp life is a function of many factors

including filament configuration and support, fill gas, on-off cycles, and wattage. The relationship between life and rated wattage is inversely proportional, i.e., the lower the wattage of the lamp the longer the life. This inverse relationship also applies to single wattage lamps operated over or undervoltage, Fig. 1-3.

The energy saving lamps on the market now make use of different fill gases. These lamps use krypton rather than argon gas used in conventional lamps. The result is a decrease in wattage without a decrease in efficacy. As an added benefit the life is increased. With these improvements, why haven't manufacturers been producing the lamps before? The incandescent lamp is still so popular because of its low cost. The energy saver lamps on the other hand are about 10 times the cost of an equivalent conventional lamp.

The human visual system responds differently to the different wavelengths of radiation. Our mind interprets these different wavelengths as color. Light sources are important in color vision because they provide the radiant energy and thus color response. The distribution of wavelengths emitted by a source is known as the SPD (Spectral Power Distribution). The significance of the SPD curve and its relationship to color and color vision are discussed in Section 1.4.2. The SPD of an incandescent lamp is shown in Fig. 8-23, page 8-20 of the *IES Lighting Handbook*[1]. Note the tremendous amount of long or red wavelengths present; this is to be expected from a source producing luminous energy by heat. Incandescent lamps have acceptable color rendition.

Although the incandescent source has a short life and low efficacy, it has advantages which make it a common choice as the light source. Among the advantages is the low initial cost of a lamp. Also the relatively small physical size makes it easy to direct the light output, because it approaches the ideal model of a "point source". As was said previously, color rendition is acceptable. Often an incandescent system is chosen because it is the easiest and cheapest to dim, an important consideration in many designs.

Tungsten-Halogen Lamps. One of the deficiencies of standard incandescent lamps has been the lumen maintenance over life. When the filament is heated, it slowly evaporates and redeposits on the inside of the bulb wall. This layer of tungsten then acts like a filter, absorbing some light and lowering the light output. This was overcome by the development of the Tungsten-Halogen Cycle lamp. More commonly known as a quartz-iodide lamp, it contains a halogen such as iodine or bromine and a fill gas. At high temperatures - the reason for the quartz envelope - the evaporated tungsten associates with a halogen molecule. Instead of being deposited on the bulb wall, the combined tungsten-halogen molecule is returned to the hot filament freeing the halogen to pick up another evaporated tungsten molecule. This cleaning action minimizes the deposit of tungsten on the bulb wall resulting in an increased lumen output throughout the life of the lamp. Fig. 1-4 shows the lumen output of a standard incandescent lamp and that of a quartz-iodide lamp over the life of each.

The main objective in developing the quartz-iodide lamp was to maintain lumen output, but other improvements were also realized. Lamp life increased slightly as did the efficacy. To operate properly, quartz-iodide lamps require relatively high temperatures and to obtain these high temperature, the filament had to be compacted and the outer envelope made smaller. The smaller source

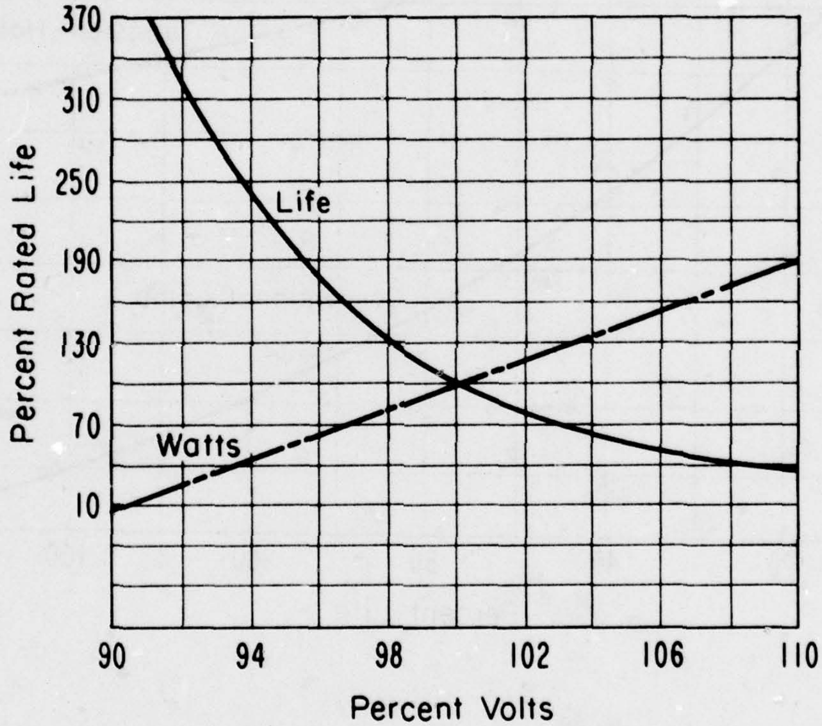

Figure 1-3 Over and Under Voltage Effect on Lamp Life

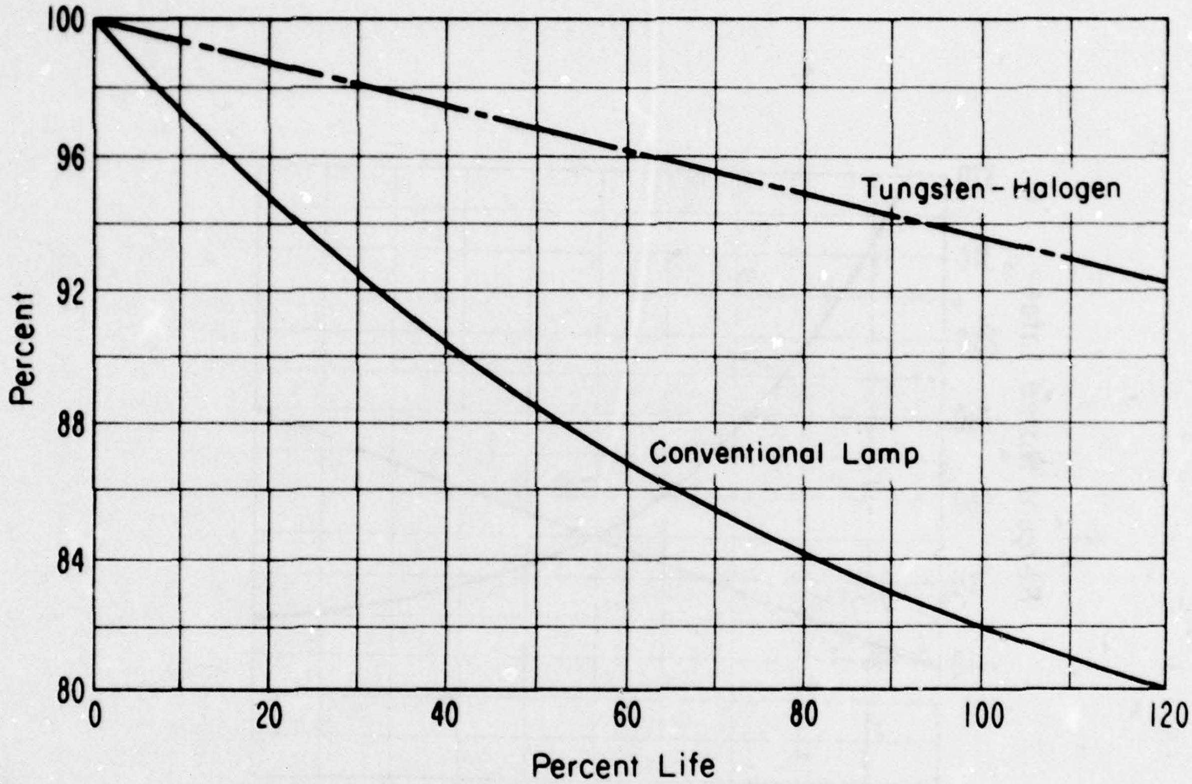

Figure 1-4 Lumen Depreciation of T-H and Conventional Lamp

more closely approaches the ideal point source needed for good optical control.

The quartz-iodide is a type of incandescent lamp and is also easily dimmed. Dimming, however, causes a reduction in bulb wall temperature which retards the uniting of the tungsten and halogen molecules resulting in bulb wall blackening and a reduction in lumen output. When the lamp is returned to a sufficient heat level, some of the tungsten deposit is removed.

The quartz-iodide SPD is similar to that of the incandescent lamp but contains slightly more of the shorter or blue wavelengths. This is a result of the higher operating temperatures.

1.2.2 Gaseous Discharge Lamps

The second category, gaseous discharge, includes those sources that produce light by passing a current through a vapor at high or low pressure. As electrons in the arc path strike an atom of the vapor, the valence or outermost electron gains energy, and moves to a higher, less stable state. When this electron returns to its normal state, it releases the added energy in the form of a photon. These photons can be in the visible or ultraviolet portion of the spectrum. To make use of the ultraviolet radiation, phosphors are used to convert it to visible radiation. The phosphors produce light in the same manner as the vapor atom struck by the electron.

The gaseous discharge method of producing light is very efficient but has the property of a negative resistance element. A negative resistance element is one in which the resistance decreases causing an increase in current, i.e., the resistance goes to zero and the current goes to infinity. To maintain the current at a safe level a ballast is used on all gaseous discharge lamps. Ballasts are not only designed to limit the current, but also to raise the power factor and provide the necessary starting voltage. Since there are numerous ballast arrangements available for the different gaseous discharge sources, any power losses in the ballast are ignored in determining the efficacy of the lamps. In the discussion of each type of lamp, examples of ballast power losses and their effect on efficacy are given.

Gaseous discharge sources are often classified as to the relative pressure within the arc tube. Fluorescent and low pressure sodium lamps are low pressure, while mercury vapor, metal halide, and high pressure sodium lamps are high pressure. The high pressure lamps are also known as HID (High Intensity Discharge) sources.

Fluorescent Lamps. The fluorescent lamp is a tube containing mercury and an inert gas, and lined with phosphors. The different bulb configurations, sizes, and electrical connections can be found in Section 8 of the *IES Lighting Handbook*[1].

The efficacy of the fluorescent lamp is quite high, up to 80 lumens/watt. Smaller, low wattage lamps have efficacies as low as 24 lumens/watt while a T12 40-watt Cool White lamp has an efficacy of 79 lumens/watt. The lamp efficacy of fluorescent lamps is also a function of the color or SPD. Of the

standard "white" lamps, the Warm White has the highest efficacy while the Natural has the lowest.

The color of a fluorescent lamp or its SPD depends on the phosphor coating on the lamp wall. There are seven "standard" colors which are common among all manufacturers. They are White, Cool White, Deluxe Cool White, Warm White, Deluxe Warm White, Natural, and Daylight. The SPD curves may be found on page 8-19 of the *IES Lighting Handbook*[1]. Special "whites" are available for specific applications or to provide radiant energy lacking in the "standard" colors. The color of lamp chosen must provide the best color rendition for the application, be readily available, and be economical.

Besides the cost of the lamp and its efficacy, lamp economics must also consider lamp life. The rated life of fluorescent lamps averages 22,000 hours.

Ballasts for fluorescent lamps are of three types: 1) preheat, 2) instant start, and 3) rapid start (RS). All fluorescent ballasts for indoor application must be thermal protected and are known as "P" ballasts. Since ballasts are inductors they hum. Sound ratings range from "A" which is the quietest to "F" which is the noisiest. Because of ballast inefficiency, they consume power, even when the lamps are removed. Although the wattage is small with no lamps, the volt-amperes is considerable. Ballast power losses lowers lamp efficacy. For example, a 40-watt lamp operated on a two lamp RS ballast has an efficacy of 67 lumens/watt compared to a lamp efficacy of 80 lumens/watt. Total power consumed by the different ballasts may be found in ballast manufacturer's catalogs.

Fluorescent lamps have other characteristics that can be a problem depending on the application. Operating on AC (alternating current), the light output of a fluorescent lamp goes to zero 120 times per second. Generally this is not noticeable, but can make high speed machinery appear to stand still. This is known as the stroboscopic effect.

The ambient temperature can cause a change in light output. Above or below a limited temperature range, the light output decreases drastically, Fig. 8-35 of the *IES Lighting Handbook*[1]. Luminaires must be designed to maintain a relatively constant ambient temperature. At low temperatures, the lamp may not even start. Besides a sufficient temperature, fluorescent lamps rely on a static charge on the bulb wall for easier starting. High humidity removes this charge and increases starting difficulty. Most lamps are now manufactured with a coating that beads up the moisture, although extremely high humidity may require the use of a double walled or sleeved lamp.

Energy saving lamps are designed to operate at a lower wattage on the same ballast as conventional fluorescent lamps. The efficacy of some is decreased while others have an increase in efficacy. Recently it has been discovered that the energy saving lamps may be the cause of premature ballast failure. While the energy saving lamps should only be considered for retrofitting an existing installation that was improperly designed and overlit, they should not be used for a new installation. They should be abandoned if they are truely causing the failure of the ballast.

Low Pressure Sodium Lamps. The low pressure sodium lamp has the highest efficacy of all sources. Producing about 180 lumens/watt, the low pressure sodium lamp is widely used throughout Europe for roadway lighting. The life of the low pressure sodium lamp is about 18,000 hours.

At the pressure at which the low pressure sodium lamp operates, sodium emits radiation at 589 and 589.6 nm (namometer). This is yellow in color and thus the color rendering of the lamp is nonexistent. All colors appear a different shade of gray or brown.

As with all gaseous discharge ballasts, the ballast of the low pressure sodium lamp lowers the lamp-ballast efficacy. The conventional ballast, an auto-leakage transformer, provides nearly constant current with an increase in lamp voltage over the life of the lamp. This causes an increase in the total power consumed over the life. The high ballast losses are due to the open circuit voltage needed for ignition of the lamp. With the auto-leakage transformer the open circuit voltage is 660 volts according to the lamp manufacturer (680 volts according to the ballast manufacturer).

A new type of ballast has been described[2] that has an open-circuit voltage only slightly higher than normal operating voltage. The ballast losses are therefore less. Also the lamp voltage rises while the current decreases during the lamp life. This results in a nearly constant circuit wattage over life. The ballast consists of a linear inductance and a saturated inductance, a capacitor, and an electronic starting circuit.

Table 1-1 gives the characteristics of a conventional ballast, while Table 1-2 gives the characteristics of the new ballast. Note that these tables are based on controlled laboratory conditions. The report did not include the performance of the new ballast at 18,000 hours of operation, probably because the testing had not progressed that far.

As can be seen, the lamp-ballast efficacy of the low pressure sodium lamp and conventional ballast is rather low. The new ballast promises to increase the system efficacy. It is not known if the new ballast is available on the market, but when it is, it will probably cost more, and have to be specifically ordered. The new ballast, although increasing system efficacy, does not correct the lamp's biggest drawback, the monochromatic SPD and subsequent yellow color.

Mercury Vapor Lamps. The mercury vapor lamp produces light by electron collisions in mercury gas at high pressure. This source has a number of different bulb shapes, wattages, and Spectral Power Distributions.

Lamp efficacy ranges from about 30 to 60 lumens/watt. Since this is a gaseous discharge lamp, it requires a ballast of which there are several versions. Table 1-3 shows nine ballasts, and the total lamp plus ballast efficacy for a 400-watt lamp. As can be seen, the total system efficacy varies widely depending on choice of ballast and is lower than lamp efficacy.

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[2]Koedam, M., DeVann, R., Verbeek, T. G., "Further Improvements of the LPS Lamp," Lighting Design & Application, Sept. 1975, pp. 39-45.

Table 1-1[2]

Conventional LPS Ballast Characteristics

Lamp Efficacy (100 hr)	188 lumens/watt
Lamp Efficacy (18,000 hr)	141 lumens/watt
Ballast Watts (100 hr)	40
Ballast Watts (100 hr per ballast manufacturer)	48
Lumens (100 hr)	33,000
Lumens (18,000 hr)	34,000
Circuit Efficacy (100 hr)	153 lumens/watt
Circuit Efficacy (100 hr using losses by ballast manufacturer)	147 lumens/watt
Circuit Efficacy (18,000 hr)	121 lumens/watt
Circuit Efficacy (18,000 hr using losses by ballast manufacturer)	114 lumens/watt

Table 1-2[2]

New LPS Ballast Characteristics

Lamp Wattage (nominal)	180
Lamp Watts (100 hr)	174
Lamp Efficacy (100 hr)	190 lumens/watt
Ballast Watts	20
Lumens (100 hr)	33,000
Circuit Efficacy (100 hr)	170 lumens/watt

Table 1-3

Ballasts for a 400-watt 277 volt Mercury Vapor Lamp

Ballast	Operating Watts	Lamp Lumens	Lamp Efficacy	Ballast and Lamp Efficacy
Reactor	471	23,000	57.5	48.9
Lag	499			46.1
Regulating	457			50.3
Auto-stabilized	499			46.1
Stabilized	499			46.1
Constant Wattage	457			50.3
CWA	457			50.3
Nonregulating	609			37.8
Premium CW	457			50.3

The mercury vapor is one of the longest lived sources, with a rated life of 24,000 burning hours. The usable life of the mercury lamp is rated at 16,000 to 18,000 hours. Beyond this the lumen output drops below an energy efficient level, Fig. 8-52 of the *IES Lighting Handbook*[1]. The lower wattage mercury lamps have a low efficacy while the higher wattage lamps have a high efficacy. The efficacy of the low wattage mercury vapor lamp is comparable to that of the incandescent lamp, however the life of the mercury vapor is approximately 12 times greater than that of the incandescent.

Clear mercury vapor lamps produce a line spectrum rather than a continuous one. The color rendition of a clear mercury vapor lamp is very poor, producing a blue-green colored light. Since one of the emitted lines is ultraviolet, the color of mercury can be altered by applying phosphors to the inside of the outer bulb or envelope. Colors available are clear, color-improved, standard white, high output white, deluxe white, and warm white deluxe. Manufacturers also market other phosphor combinations, but in general deluxe white and warm white deluxe provide the best color rendition and flattery to skin tones.

When a mercury vapor is turned on, the arc stream builds to full intensity over approximately 10 minutes. When it is turned off or the voltage drops below a level necessary to sustain the arc, the lamp must cool down before reignition can occur. The restart time for a typical mercury vapor lamp is from 3 to 6 minutes. In some situations, a backup source may be required to maintain illumination until the mercury can start again.

Recent developments for mercury vapor include dimming capability and electronic ballasting (see Section 3.2.1 for dimmers available). Electronic ballasts have been researched since the mercury vapor lamp first appeared. A number of problems remain, including the high cost, but it is known that with an electronic ballast, lamp efficacy and total system efficacy are increased significantly. Other advantages expected of the electronic ballast are smaller size and weight, lower noise, increased lamp life, and easier dimming.

Metal Halide Lamps. An improvement on the mercury vapor lamp was made with the addition of halide salts to the arc tube. The resulting lamp, the metal halide, has become one of the best sources. The clear mercury lamp produced distinct lines of radiation with very little in between. The addition of halides, such as sodium, thorium, scandium, and indium that produce their own SPD, smooth out the lamp SPD over the visible spectrum. Three SPD curves of different halide mixtures can be found on page 8-20 of the *IES Lighting Handbook*[1].

The addition of the halides not only improved the color rendition, but also increased the efficacy. Metal halide efficacies average 100 lumens/watt. Table 1-4 shows three metal halide ballasts, the lamp efficacy, and total system efficacy. The decrease is less than that for mercury vapor lamps and associated ballasts.

Life of a metal halide lamp is somewhat less than an equivalent mercury vapor, averaging about 16,000 hours for the various wattages.

Table 1-4

Ballasts for a 400-watt 277 volt Metal Halide Lamp

Ballast	Operating Watts	Lamp Lumens	Lamp Efficacy	Ballast and Lamp Efficacy
Regulating	485	40,000	100	82.5
Auto-stabilized	471	40,000	100	84.9
Lead Peak Auto	471	40,000	100	84.9

The most significant improvement of the metal halide is the color rendition. As was pointed out previously, the SPD, although a line spectrum, covers more of the spectrum without the use of phosphors. Since the light source is the arc tube, not the entire envelope, better optical control can be achieved with good color rendition. Although the metal halide lamp provides light energy of good color rendering ability, the lamps themselves can appear to be tinted differently. When sources are visible and in close proximity this color difference can be annoying. Since aging is one cause of the color shift, the color difference can be reduced by group relamping.

As with mercury vapor lamps, it takes a few minutes for the lamp to come to full light output, and it must cool down before it can be restarted. The restrike time for the metal halide is 10 to 15 minutes. Dimming equipment and electronic ballasts are being developed and are available from one manufacturer.

High Pressure Sodium Lamps. The high pressure sodium lamp's radiation is spread out across the spectrum rather than being limited to two bands as in the low pressure sodium lamp. For the high pressure sodium lamp, efficacy averages 125 lumens/watt with a rated life of 20,000 hours.

An SPD curve is shown on page 8-20 of the *IES Lighting Handbook*[1]. Color rendition under this light source is fair to good. Most commonly used outdoors in roadway and parking lot lighting, it is being used more for indoor applications. When used indoors some precautions should be taken. Since no phosphors are needed for color correction, the size of the source, the arc tube, is rather small. This allows for good optical control, but also concentrates the light in a minimal area causing a potential glare source if not shielded properly. Because the SPD is not uniform, but dominant in the orange region of the spectrum, object colors should be carefully chosen to take into account the color deficiencies of the high pressure sodium lamp.

The warmup time for these lamps is shorter than that for mercury vapor or metal halide lamps, and the lamp does not need to cool down before the arc can be restarted. The restrike time for the high pressure sodium lamp is 1 minute.

1.2.3 Summary

The eight light sources just discussed represent the major sources for artificial lighting. The factors that are important in choosing which of these to use are efficacy, life, color rendering ability, and source size. Dimming ability is also a consideration, but systems are available or being developed for all sources. To better evaluate the sources Table 1-5 compares them on an equal wattage basis and Table 1-6 compares them on equal lumen output. Note the efficacies given are lamp efficacies only, and do not include ballast losses if any.

1.3 LUMINAIRES

Luminaires are equipment that house the light source and its related electrical equipment, and direct the light to where it is needed. This section discusses the means of controlling light, the measurement of the output of a

Table 1-5

Source Comparison Based on Equal Watts (400 watts)

Lamp	Design	Quantity	Watts (Total)	Lumens (each)	Source Efficacy (each)	BTUH (Total)	Life HRS (each)	Cost (Total)
Incandescent	100A19	4	400	1740	17.4	1364	750	(.50) 2.00
Tungsten-Halogen	Q400T4/CL	1	400	7500	18.8	1364	2000	16.25
Fluorescent	F40CW	10	400	3150	78.9	1364	20000	(1.67) 16.70
L.P. Sodium	SOX135	3	405	21500	159.3	1381	18000	(40.00) 120.00
Mercury Vapor	H33GL-400/DX	1	400	22500	56.3	1364	24000+	15.50
Metal Halide	M400/BU-HOR	1	400	34000	85.0	1364	15000	34.50
H.P. Sodium	LV400/BU	1	400	50000	125.0	1364	20000	60.00

+Rated Life = 24000 hrs, Usable Life = 16 - 18000 hrs.

Table 1-6

Source Comparison Based on Equal Lumens (30,000 lms)

Lamp	Design	Quantity	Lumens (Total)	Watts (each)	Source Efficacy (each)	BTUH (Total)	Life HRS (each)	Cost (Total)
Incandescent	100A19	17	(1740) 29580	100	17.4	5797	750	(.50) 8.50
Tungsten-Halogen	Q400T4/CL	4	(7500) 30000	400	18.8	5456	2000	(16.25) 65.00
Fluorescent	F40CW	10	(3150) 31500	40	78.9	1364	20000	(1.67) 16.70
L.P. Sodium	SOX180	1	33000	180	183.3	614	18000	60.00
Mercury Vapor	H37KC-250/OX	2	(13000) 26000	250	52.0	1705	24000+	(18.75) 37.50
Metal Halide	M400/BU-HOR	1	34000	400	85.0	1344	15000	34.50
H.P. Sodium	LU250/BU/S	1	30000	250	120.0	853	15000	64.00

+Rated Life = 24000 hrs, Usable Life = 16 - 18000 hrs.

luminaire, the factors affecting its in-place performance, and the cost.

1.3.1 Light Control

The light sources discussed in the previous section provide us with a source of luminous flux. This flux is not necessarily directed where it will do the most good. For example, a bare incandescent lamp radiates in all directions.

To control or redirect the light where we want it, materials are used that have one or more of the three basic properties: transparency, translucency, or opacity. Transparent materials will pass or transmit all or most of the light incident on them. Translucent materials will also transmit most incident light, but will scatter it as it is transmitted. Opaque materials on the other hand will transmit no light, reflecting or absorbing it.

When light strikes a material that has any one of the above properties it can be reflected, transmitted, refracted, absorbed, or polarized. It is by one of these phenomena, or a combination of them that light can be manipulated.

Reflection. The first method for controlling light, reflection, occurs in many forms - regular or specular reflection, spread reflection, diffuse reflection, mixed reflection, scattered reflection, and selective reflection.

Regular or specular reflection is the type which occurs in mirrors or highly polished metals. In such cases, the angle of reflection equals the angle of incidence as in Fig. 1-5a.

Spread reflection is similar to specular reflection except the light is scattered about the ray at the angle of reflection Fig. 1-5b.

Diffuse reflection is exhibited by matte white paper or flat white paint. A perfect diffuser would obey Lambert's Cosine Law which states that the Intensity reflected at angle θ is equal to the Intensity reflected normal to the surface times the cosine of the angle θ. The reflection pattern then is not a function of the angle of incidence. This is shown in Fig. 1-5c.

Mixed reflection is a combination of specular, spread and diffuse reflection. Mixed reflection probably best describes real materials, Fig. 1-5d.

Scattered reflection is that which cannot be associated with either Lambert's Cosine Law or the Law of Regular Reflection. Fig. 1-5e shows a possible reflection pattern.

Selective reflection gives objects their color by the phenomena called selective absorption (Section 1.4.4). Certain wavelengths of incident radiation are absorbed by the surface while others are reflected. This selection of which wavelength to reradiate determines the color of the object. Selective reflection can have any of the reflection patterns previously mentioned.

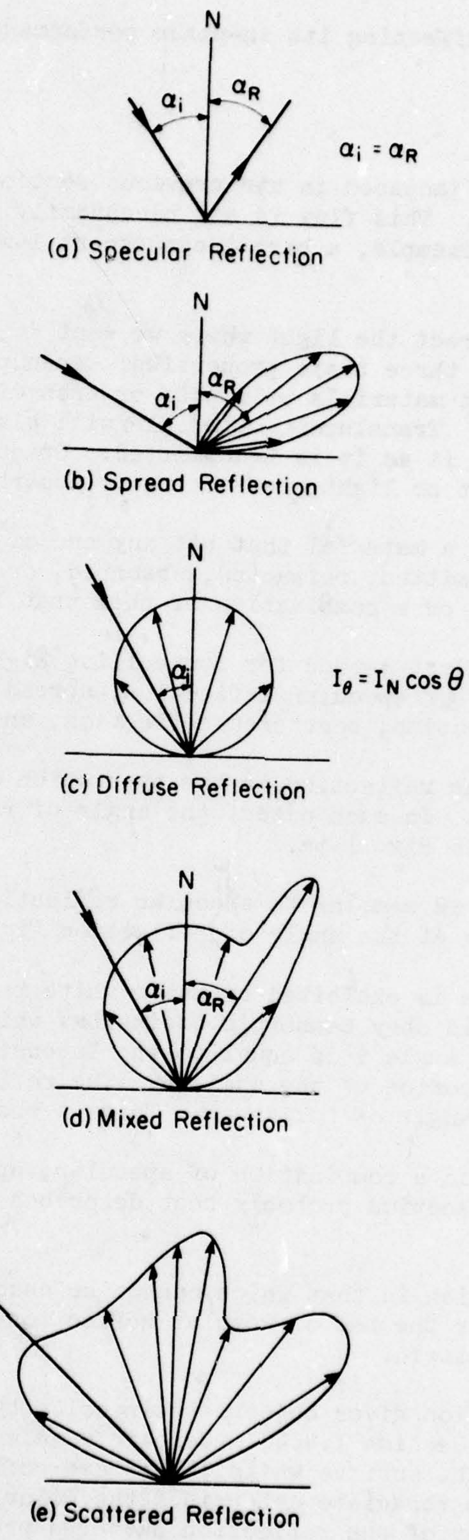

Figure 1-5 Reflection Pattern

Generally, specular reflection is used to control light. There are four specific contours used in reflective light control - the flat plane, the circle, the parabola, and the ellipse. These basic shapes can be configured in numerous ways to direct light. For a flat plane, all incident rays are reflected at an angle equal to the angle of incidence. If the incident rays are parallel, the reflected rays will be parallel. For a circular reflector with the source at the center all reflected rays return through the center. If the source is placed ahead of the center, the reflected rays will diverge as in Fig. 1-6a. Probably the best known reflector shape is the parabola. If the light source is placed at the focal point of a parabolic reflector, all reflected rays will be parallel Fig. 1-6a. This is the principle used in spotlights to obtain a beam of parallel light rays. The final shape is the ellipse. With an ellipsoidal reflector, a source at the first focal point of the ellipse causes the reflected rays to pass through the second focus in Fig. 1-6c. This principle is used in the pinhole spot where a wide pool of light is desired from an instrument with a small opening or aperture.

Transmission. Transmission of light through specific materials occurs in patterns similar to light reflected off materials. The types of transmission are regular, spread, diffuse, mixed, scattered, as well as selective. Each type produces a distribution like the corresponding reflection.

Refraction. Snell discovered that as light travels from one media to another its speed changes slightly. As a consequence, the light rays are bent. This is known as refraction, and follows Snell's Law,

$$n_1 \sin\alpha_1 = n_2 \sin\alpha_2$$

where n is the index of refraction and

α is the angle between the normal to the surface and the ray

This is illustrated in Fig. 1-7.

The phenomenon of refraction is used in lenses and prisms to bend light. Many books are written on optics and lens design; and therefore, the reader is referred to them for more on refraction[3,4].

Absorption. In reality all materials, whether they transmit or reflect light, absorb some of the energy. Absorption can be either selective or non-selective. Selective absorption, as was stated earlier is what occurs causing

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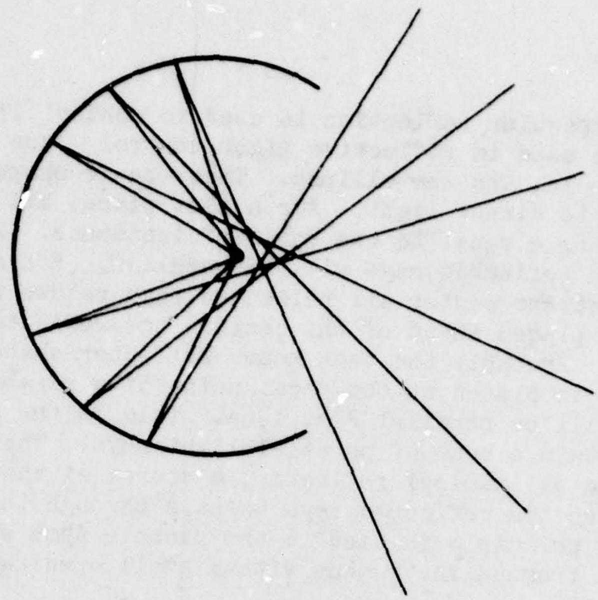
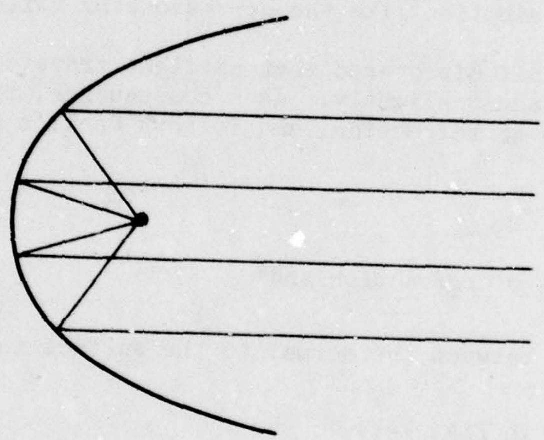
[3]Kingslake, R., Applied Optics and Optical Engineering, Academic Press, New York, 1965.

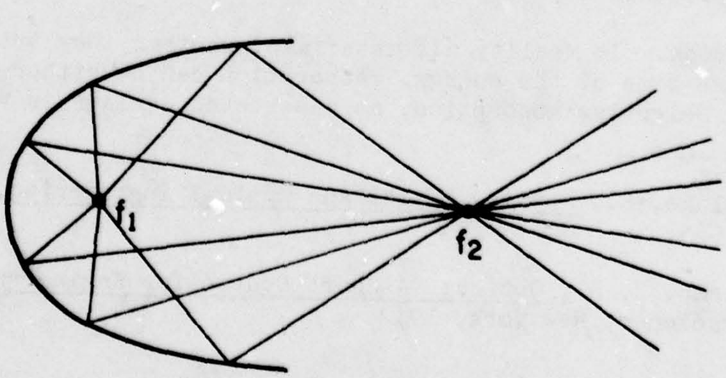
[4]Williams, C. S., Optics: A Short Course for Engineers and Scientists, Wiley-Interscience, New York, 1972.



(a) Circular Reflector



(b) Parabolic Reflector



(c) Elliptical Reflector

Figure 1-6 Reflector Shapes

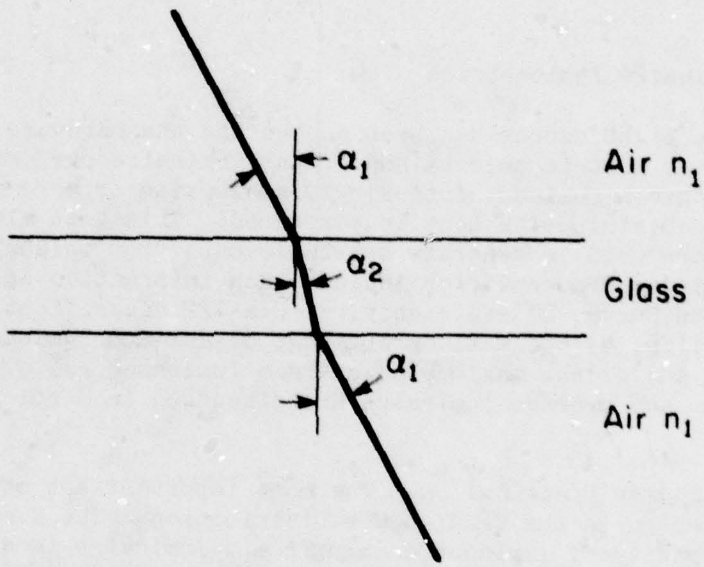


Figure 1-7 Refraction

objects to have color. Nonselective absorption, on the other hand, does not affect the color of the material. All wavelengths are absorbed equally in nonselective absorption causing a change in intensity. An example of non-selective absorption in a transmitting material is a neutral density filter.

Polarization. Light is composed of waves oscillating in an infinite number of planes perpendicular to the direction of propagation. Certain materials reflect or transmit only a portion of all those waves. This light is said to be polarized.

Fig. 6-16 of the *IES Lighting Handbook*[1] is a representation of unpolarized light. When unpolarized light passes through a polarizing material, such as that found on many sunglasses, only certain waves pass. Those that are blocked depend on the orientation of the polarizer Fig. 6-16 and 6-18 in the *IES Lighting Handbook*[1].

1.3.2 Luminaire Photometrics

Once a light source has been chosen and the hardware designed to direct the light, it must be ascertained if the luminaire performs as intended. To determine this a Luminous Intensity Distribution or more commonly known as a Candlepower Distribution test is performed. This test along with maximum luminance are used to generate the basic data from which luminaire photometrics are determined. Photometrics include such information as 1) the Candlepower Distribution Curve, 2) efficiency, 3) CIE-IES classification, 4) Coefficients of Utilization, 5) the maximum spacing, 6) maximum luminance, 7) average luminance, and 8) the maximum to average luminance ratio. The luminance ratio and maximum and average luminance are discussed in Section 1.4.1 *Direct Glare (VCP)*.

Candlepower Distribution. The most important set of data in artificial lighting design is the Candlepower Distribution. The Candlepower Distribution is the intensity of luminous energy from a luminaire in a particular direction. Fig. 1-8 is a plot of Candlepower Distribution. This curve is the luminous intensity data (the radial dimension) plotted against a vertical angle measured from nadir on a polar coordinate system for a particular plane through the luminaire. The center of the plot is the center of the luminaire and nadir is defined as straight down from that point. Ideally the intensity at an infinite number of vertical and horizontal angles should be measured. Since this is impractical, a number of vertical planes and the vertical angles in those planes are defined for Candlepower Distribution measurements. The minimum number of vertical planes for an assymetric distribution is three, 90° to the lamp axis, 45°, and 0° or parallel to the lamp axis. Two other planes should be measured, 22.5°, and 67.5°, for greater accuracy. The minimum number of vertical angles should be at 10° steps. Preferably, vertical angles should be at 2-1/2° steps. Fig. 1-9 is a plan view of a 2- by 4-foot fluorescent luminaire showing the vertical measurement planes; the vertical angles or steps are indicated in Fig. 1-8.

Luminaire Efficiency and Classification. Two criteria by which to judge luminaires are their efficiency and their CIE-IES classification. The efficiency is a ratio of the amount of light that the luminaire puts out to

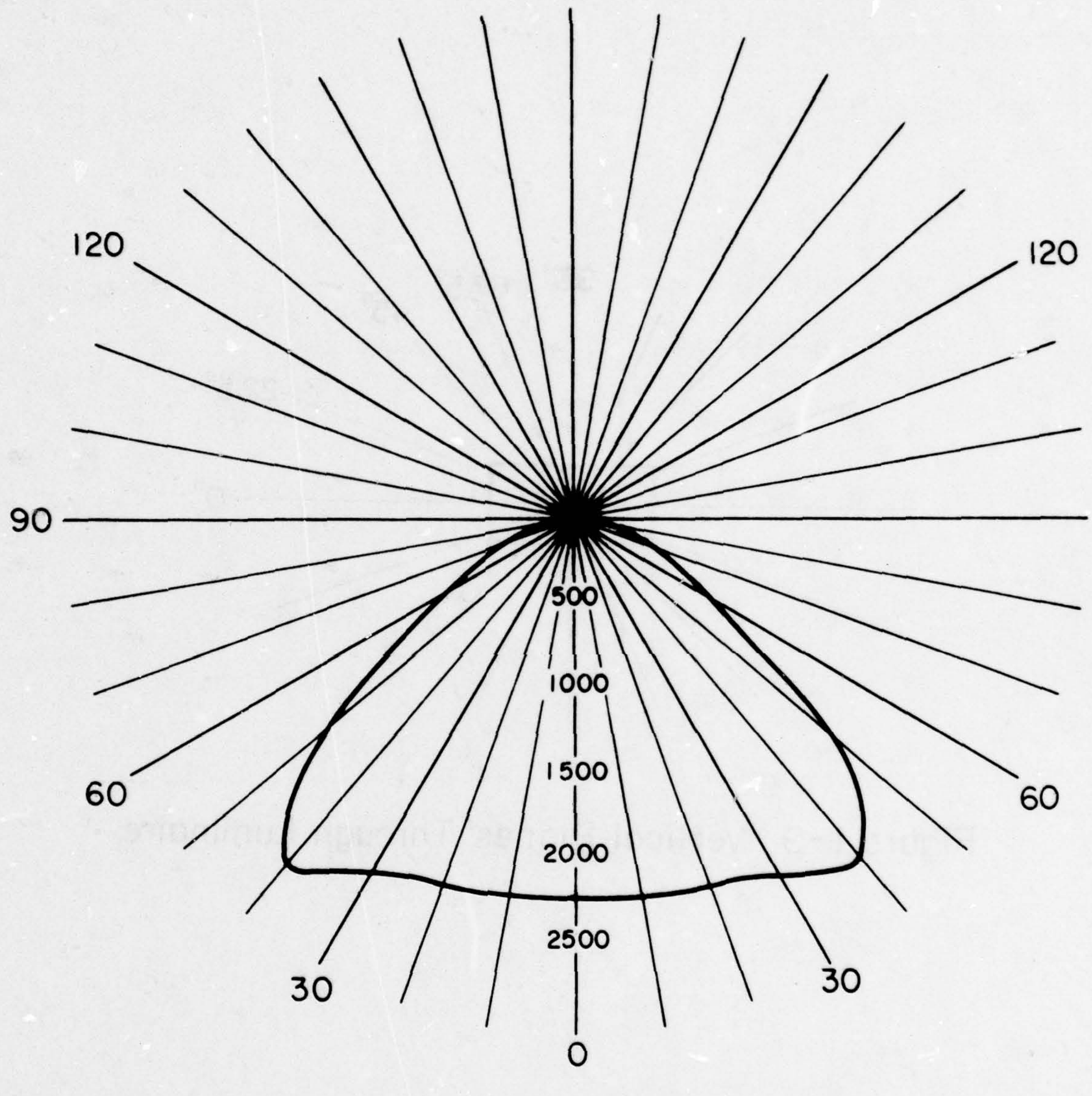


Figure 1-8 Luminous Intensity (Candlepower) Distribution Curve

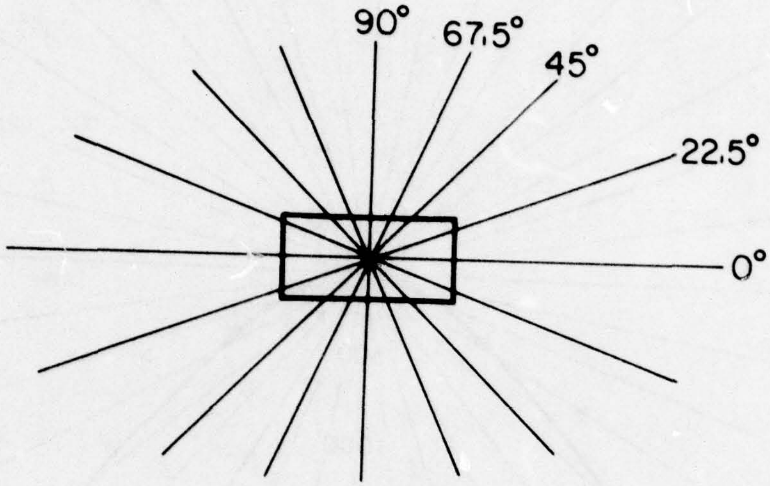


Figure 1-9 Vertical Planes Through Luminaire

that produced by the bare light sources. Luminaire efficiency does not indicate where that flux is directed, which is the purpose of the CIE-IES classification system.

The CIE-IES classification system describes a luminaire by the percentage of light in the upper and lower hemispheres of the Candlepower Distribution Curve. The six categories of the CIE-IES classification (Fig. 1-10) are: Direct, Semi-Direct, Direct-Indirect, General Diffuse, Semi-Indirect, and Indirect. The General Diffuse has a horizontal component, while the Direct-Indirect (not recognized by the CIE) has very little horizontal component.

To be able to determine either efficiency or the CIE-IES classification of a luminaire it is necessary to determine the total amount of light radiated in each hemisphere. This is done by calculating the zonal lumens produced by the luminaire.

Taking a unit sphere and dividing it into horizontal slices as in Fig. 1-11, the surface area of each strip can be calculated.

$$A_s = [2\pi(\cos\theta_2 - \cos\theta_1)]$$

This area, A_s, is known as the Zonal or Lumen Constant for the zone between θ_1 and θ_2. The Zonal Constants for 1, 2, 5, and 10 degree zones may be found on page 4-18 of the *IES Lighting Handbook*[1]. Furthermore from the definition of Luminous Intensity.

$$I = \frac{d\phi}{d\omega}$$

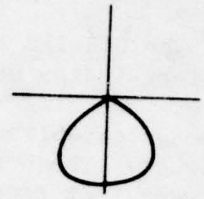
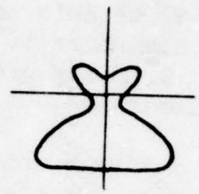
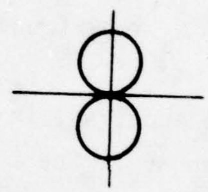
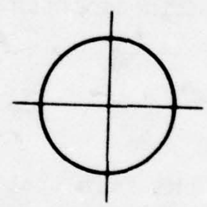
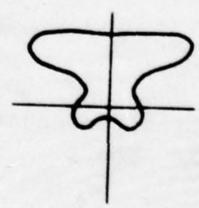
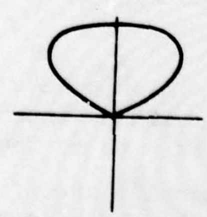
and the fact that we are using a unit sphere $(r = 1)$

$$\omega = A_s/r^2 = A_s$$

we obtain an equation to calculate the flux through a zone whose area is A_s on a unit sphere.

$$\phi = IA_s$$

To calculate the flux, ϕ, we need the area which is a Zonal Constant and the luminous intensity or candlepower. The luminous intensity, I, for a zone is taken to be the value of the intensity halfway between θ_1 and θ_2 for each vertical plane of the luminaire measured. This is known as the AMZC (Average Mid Zonal Candlepower). For example, to calculate the flux in the zone between 45° and 55° of a luminaire with 5-plane photometry the AMZC would be the sum of I at 50° for the 0° plane, 2I at 50° for the 22.5° plane, 2I at 50° for the

Classification	% Up Light	% Down Light	Typical Candlepower Distribution Curve
Direct	0-10%	90-100%	
Semi-Direct	10-30%	60-90%	
Direct-Indirect*	40-60%	40-60%	
General Diffuse	40-60%	40-60%	
Semi-Indirect	60-90%	10-30%	
Indirect	90-100%	0-10%	

*IES Classification Only

Figure 1-10 CIE-IES Classification

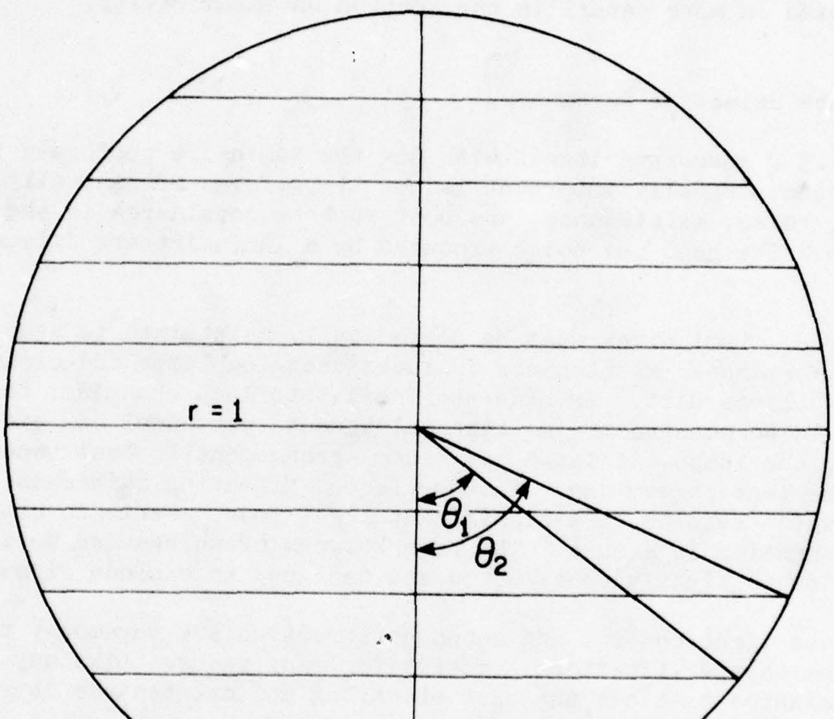


Figure 1-11 Unit Sphere For Calculating Zonal Constants

45° plane, 2I at 50° for the 67.5° plane, and I at 50° for the 90° plane divided by eight. An example can be found in Appendix A.

Once the lumens for each zone are calculated they are summed for the zones 0°-90° and 90°-180° to determine the CIE-IES classification. The total lumen output calculated is compared to the total bare lamp lumen output to determine the luminaire efficiency.

Coefficients of Utilization and Maximum Spacing Ratios. Coefficients of Utilization and maximum spacing ratios are calculated from the Candlepower Distribution. These two parameters are used in the lumen method of design and are discussed in more detail in the section on Zonal Cavity.

1.3.3 Luminaire Selection Parameters

Section 1.3.2 concerned itself with how the luminaire performed its lighting function. Equally important is how it performs mechanically. Such items as heat, noise, maintenance, and cost must be considered in the choice of a luminaire. The heat and noise produced by a luminaire are discussed in Section 1.7.

Maintenance. Luminaires must be periodically maintained to keep them at their peak performance. Maintenance includes changing lamps and cleaning the surfaces that collect dirt. In order to facilitate lamp changing, the luminaire should be constructed so that maintenance personnel can easily and rapidly get to the lamps. A latch and hinge arrangement is best because handling of the lens is avoided. Another factor affecting maintenance is dirt accumulation which results in a significant light loss. Periodic cleaning of any type of luminaire is a must. The time between cleanings can be lengthened if the luminaire is tightly constructed and designed to exclude airborne dirt.

Cost. Good light control and sound construction are paramount to a lighting system that will perform properly for many years. Like any item of quality, a luminaire that has the best operating and maintenance characteristics is usually the most expensive.

Additional Factors in Selection. There are numerous additional factors, such as comfort, appearance, light source, application, etc., involved in the selection of a luminaire. Multiply this by the number of manufacturers and one has many thousands of luminaires from which to choose. A system proposed by Helms[5] would computerize the factors involved, and selection of luminaires could be made based on parameters input by the designer.

1.4 VISUAL COMFORT AND VISIBILITY

1.4.1 Glare

To have a luminous environment that is visually comfortable, the occupants

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[5]Helms, R. N., "Luminaire Selection and Design - An Alternative to Manufacturers' Catalogs," Lighting Design & Application, August 1974, pg. 26.

must not see any glare. Glare is defined as the result of excessive luminances in the field of view that are greater than the luminance to which the visual system is adapted. Physical discomfort (discomfort glare) or loss in visual performance and visibility (disability glare) can result from glare in the visual field.

There are many factors involved in producing glare. One is the length of time that the high luminance is present. Another factor is the luminance ratios between the glare source and the surround in the major portion of the field of view. The task involved is another factor in glare. Important elements that cause glare are the light source, its size, luminance, position, and surround luminance. A very small bright source directly in the line of sight against a dark surrounding is an example of exaggerated glare.

Glare is complex and can be categorized into two major types - Direct and Indirect. Direct glare is due to excessively bright sources of light (luminaires and/or windows) in the field of view which shine directly into the eyes; indirect glare is due to light sources that are reflected from tasks into the eyes.

DIRECT GLARE (Visual Comfort) (Discomfort Glare)	INDIRECT GLARE (Visibility) (Disability Glare)
Direct Glare	Reflected Glare
	Veiling Reflection

Direct glare is associated with "heads-up" tasks (Fig. 1-12), i.e. the glare is produced by excessive luminances in the visual field that affect the visual system as the individual looks around the environment. Indirect glare is associated with "heads-down" tasks. As the individual looks down at his work surface, indirect glare acts to create discomfort and/or a loss in visibility due to the action of the luminous environment on the task.

Relative to the luminaire, the direct glare zone is associated with luminous intensity produced in the zone from 45° to 90°, while indirect glare is affected by luminous intensity produced in the zone from 0° to 45° (Fig. 1-12).

Direct glare (heads-up tasks) is evaluated in terms of VCP (Visual Comfort Probability) while indirect glare (heads-down tasks) is evaluated in terms of ESI (Equivalent Sphere Illumination). Direct glare and indirect glare present two opposing problems. To minimize direct glare the luminous intensity should be kept out of the 45° to 90° zone, which means it is placed in the indirect glare zone. To minimize indirect glare, the luminous intensity should be kept out of the 0° to 45° zone which means it is placed in the direct glare zone.

The designer must evaluate each room on the basis of the tasks performed to determine which type of glare is the greater problem. In general, it is difficult to optimize the solution to both direct and indirect glare resulting in trade-offs.

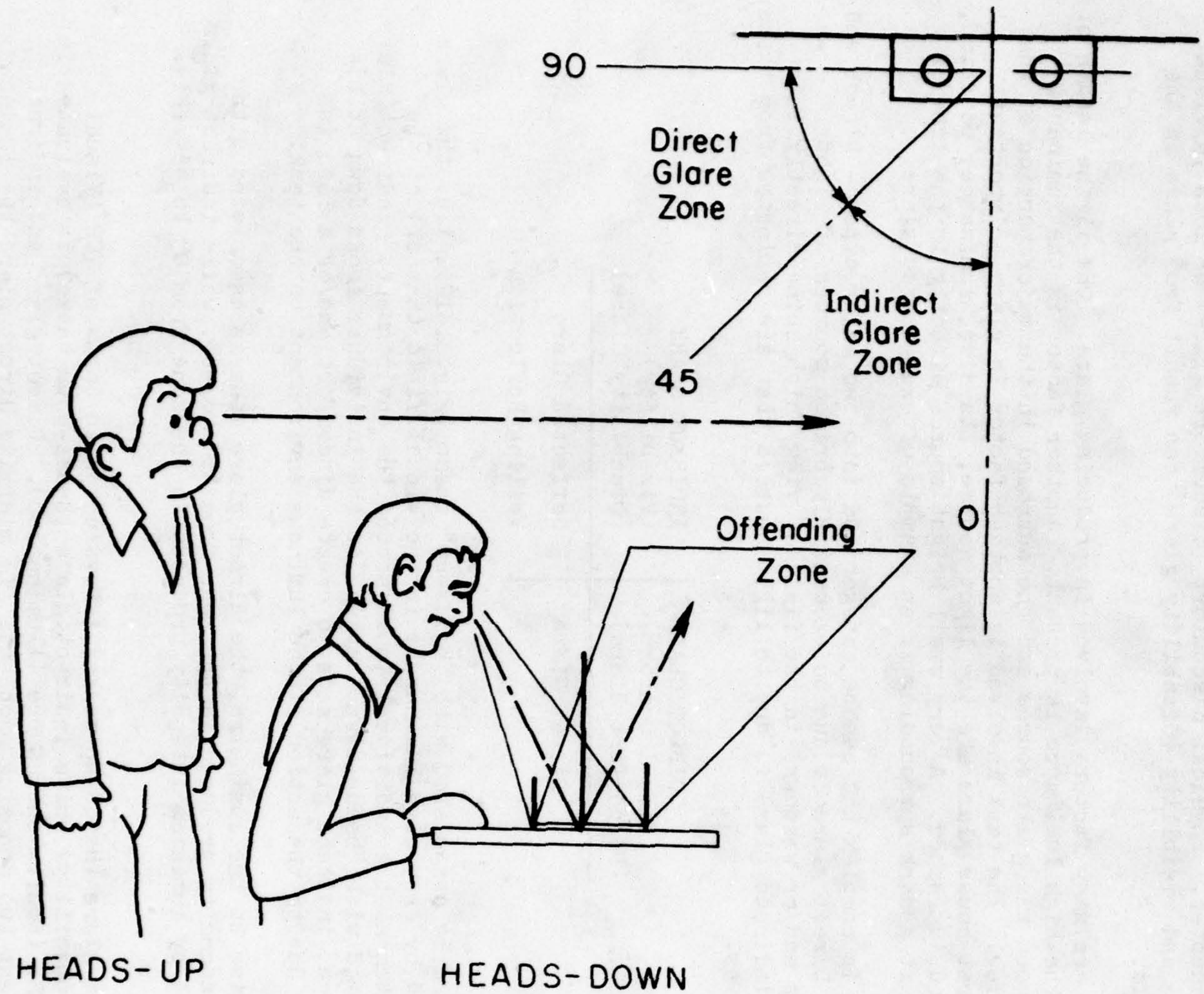

Figure 1-12 Direct and Indirect Glare

Indirect glare involves two forms of glare: 1) Reflected Glare and 2) Veiling Reflections. Reflected glare is caused by specular or glossy surfaces reflecting images of bright sources into the eyes. Not as apparent as reflected glare, veiling reflections occur on surfaces reducing the contrast of the task. The major problem with veiling reflections is that they are not visible, yet they reduce contrast and thus visibility.

Direct Glare (VCP). Direct glare is largely dependent on the characteristics of the room and the light sources in the field of view. The Direct Glare Committee of the RQQ Committee[6] of IES states that "Direct Glare may not be a problem in lighting installations if all three of the following conditions are satisfied":

1. The VCP is 70 or more.
2. The ratio of maximum-to-average luminaire luminance does not exceed five to one (preferably three to one) at 45°, 55°, 65°, 75°, and 85° from nadir crosswise and lengthwise.
3. Maximum luminaire luminances crosswise and lengthwise do not exceed the following values.

Angle	Max. Lum. (fL)
45°	2250
55°	1602
65°	1125
75°	750
85°	495

An initial judgement of the direct glare potential of a luminaire can be made by examining the maximum and average luminances at the angles above 45° from nadir. A number of methods of evaluating direct glare have been devised. (VCP) Visual Comfort Probability is the method currently accepted by the IES for evaluating glare in a room. The VCP value represents the percentage of people that probably will not complain about the glare produced in the space.

The VCP method involves a luminaire-by-luminaire determination of a discomfort index for each luminaire within the field of view. The individual indices are then combined in an appropriate manner to obtain an overall rating called the DGF (Discomfort Glare Factor). To obtain the numerical VCP the overall rating (DGF) is entered on a graph to determine VCP. Refer to "Computing Visual Comfort Ratings for a Specific Interior Lighting Installation"[7] for a more detailed description of the VCP method.

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[6]Committee on Recommendations of Quality and Quantity of Illumination of the IES, "Outline of a Standard Procedure for Calculating Visual Comfort Ratings for Interior Lighting - Report No. 2," Illuminating Engineering, October 1966, pp. 643-666.

[7]Guth, S. K., "Computing Visual Comfort Ratings for a Specific Interior Lighting Installation," Illuminating Engineering, October 1966.

Comfort is a property of the individual and, therefore, a wide variable. Therefore, this comfort rating system should act as a guide to a quality design. The VCP method assesses visual comfort that is related to discomfort (discomfort glare) which is commonly associated with direct glare.

The computation of VCP for a room is dependent on the following factors:

1. Room size and shape
2. Surface reflectances
3. Illumination level
4. Luminaire type, size, and distribution
5. Number, location, and orientation of luminaires
6. Luminance of the entire visual field
7. Observer location and line of sight
8. Differences in individual glare sensitivity
9. Equipment and furniture

Two ways to obtain a VCP for a room exist--calculation or table. Naturally, the VCP at any point can be calculated, either by hand using the method described by Guth[7] or a computer program[8]. The second way is to obtain a VCP table from the manufacturer who has already calculated it for a standard set of conditions and his luminaires. Fig. 1-13 shows a typical rectangular room. To facilitate comparison of VCP calculated by different manufacturers, the following standard conditions have been established:

1. Initial illumination level of 100 fc (footcandles). (Number of luminaires determined by Zonal Cavity Method.)
2. Surface reflectances: 80% ceiling, 50% walls, and 20% floor.
3. Mounting heights of 8.5, 10, 13, and 16 feet.
4. A range of room dimensions.
5. Standard layout of luminaires uniformly distributed in the room. (Room is divided into 5 by 5 foot modules and the total number of luminaires from standard condition 1 are divided among the total number of modules (Fig. 1-13).
6. An observation point 4 feet in front of the center of the rear wall and 4 feet above the floor (which is assumed to be the worst).
7. A horizontal line of sight directly forward.
8. A limit of the visual field to 53° above and directly forward from the observer.

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[8]DiLaura, D. L., "On the Computation of Visual Comfort Probability," Journal of the Illuminating Engineering Society, July 1976.

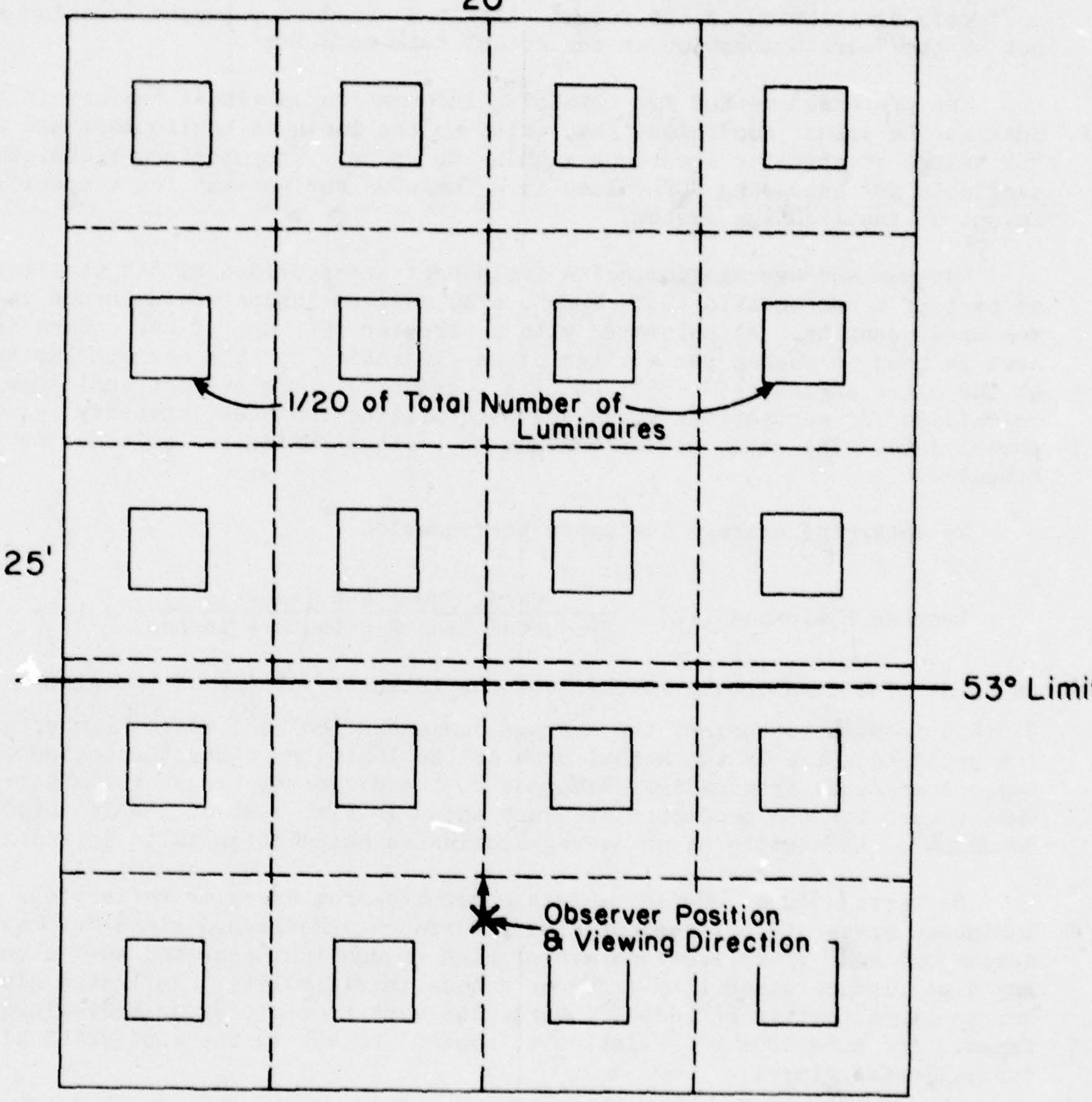

Figure I-13 Typical Room for Calculating VCP Tables

Standard tables can be used to make a preliminary evaluation of effects of direct glare on visual comfort. However, the tables are too general to allow an accurate assessment of glare especially if a task lighting approach is utilized because of standard condition 5, i.e. "standard layout of luminaires uniformly distributed in the room." Also the standard observer location may not be the "worst" location or the actual task location[9].

The preferred method for obtaining information on visual comfort is to analyze the actual conditions that exist in the luminous environment and obtain VCP values at specific locations within the space. Computerized techniques are available for assessing VCP values in a luminous environment for a specific layout of the lighting system.

Maximum and average luminaire luminances are provided by the manufacturer as part of a photometric test report. The maximum luminaire luminance is a measured quantity. A photometer with a circular aperture of one square inch area is used to search the surface of the luminaire for the maximum luminance at the glare angles (45°, 55°, 65°, 75°, and 85°). The average luminance is calculated for each of the glare angles utilizing luminous intensity (candlepower) data. The ratio of the maximum to average luminaire luminance is computed.

To determine average luminance the equation

$$\text{Average Luminance (fL)} = \frac{\text{Candlepower @ } \theta \text{ (candela)}}{\text{Projected Area @ } \theta \text{ (square inches)}} \times 144\pi$$

is used. The candlepower is the luminous intensity at one of the glare angles, θ; 144π is used to convert the average luminance (cd/in^2) to footLamberts (fL). The projected area is the actual area of the luminaire times the cosine of the angle θ measured from nadir. Examples of the different types of luminaires and what to use for the projected area are shown in Fig. 3-36 of the *IES Lighting Handbook*[1]. An example of an average luminance calculation is in Appendix A.

Reflected Glare. Reflected glare results from specular reflections of high luminance areas off polished or glossy surfaces. Reflected glare may cause discomfort and, if reflections are of high enough luminance and sufficient size, may also produce disability glare or a loss in visibility. Reflected glare is due to light that is reflected towards the eyes from glossy or semi-glossy surfaces. The zone from 0° (relative to source) to 45° is the most critical area for reflected glare.

The bright patches of light on the task are images of the light sources. The less specular or reflective the surface is, the less distinct the image will appear. The distinct image of a bright source is more glaring than the image of a diffuse source. Reflected glare is very distracting, annoying, a source of discomfort, and causes a reduction in contrast. The effects of

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[9]Florence, N., "Comparison of the Energy Effectiveness of Office Lighting Systems," A paper presented at the 1976 IES Annual Technical Convention, Cleveland, Ohio.

reflected glare are more serious if the task surround is dark due to the luminance ratio. Specular images in a highly-polished dark walnut desk are much more harsh than they would be if reflected from a well-polished light colored desk.

Veiling Reflections (ESI). Veiling reflections are any reflections that veil the task with reflected light resulting in a reduction of contrast. Veiling reflections are most commonly associated with light reflected off of matte or diffuse surfaces. The reduction in contrast results in a loss in visibility and visual performance.

The contrast of a task is the difference in luminance between an object (print) and its background (paper).

$$C = \left| \frac{L_O - L_B}{L_B} \right| \quad \text{Blackwell Formula (Fig. 1-14)}$$

where C is the contrast,
L_O is the luminance of the object, and
L_B is the luminance of the background

The luminous environment interacts with the task causing a change in the task contrast which affects the visibility of the task. This effect of veiling reflections on task contrast is evaluated in terms of ESI (Equivalent Sphere Illumination).

An understanding of ESI can best be achieved by making use of an example. If the reader needs an in-depth understanding of the research that went into the development of the ESI method, the *IES Lighting Handbook*[1] gives most of the references. However, an understanding of the following example is sufficient for an understanding and application of the ESI method.

Example Statement:

At a given viewing angle, in a particular orientation, for a given task, in this luminous environment, at this point, a value of 50 ESI footcandles is calculated. At that same point, an ordinary footcandle meter is placed and it reads 100 footcandles.

50 ESI footcandles - calculated

100 footcandles - measured or "raw"

What does this mean?

If one were to take the task and place it inside a photometric sphere it would require only 50 footcandles of illumination inside the sphere to produce the same visibility that the 100 footcandles produce in the real environment.

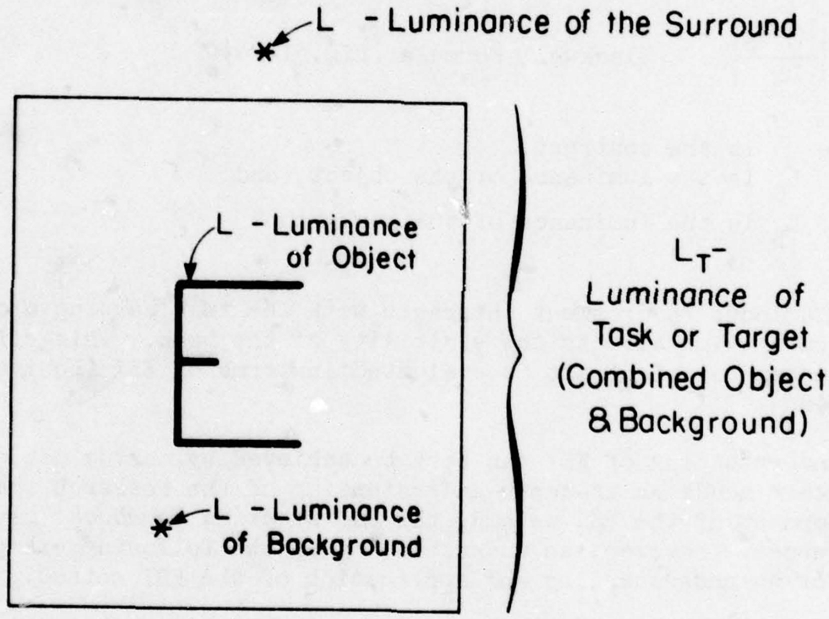

Figure 1-14 Definition of Luminance of Object, Background, Task and Surround

What is a photometric sphere?

It is a large hollow sphere painted inside with a special high reflectance diffuse white paint. Light is introduced through an aperture in the side of the sphere. The light strikes a dispersion cone causing the light to reach the task after multiple reflections within the sphere. A second aperture is placed in the sphere at a given viewing angle to allow for the measurement of L_B and L_O produced in the sphere.

Why a photometric sphere?

1. A photometric sphere is simply a reference or standard lighting condition.

2. It is an easily reproducible standard.

3. It produces uniform diffuse light which is similar to the lighting conditions used in the basic research.

It is important to remember that a photometric sphere was not selected because it was better than any other lighting system. It is not necessarily the ideal or the best possible lighting. It is a reference lighting condition only!

It is possible and desirable to have higher ESI footcandles than ordinary footcandles.

100 ESI footcandles - calculated

50 footcandles - measured (ordinary footcandles)

Ordinary footcandles are related directly to the watts consumed so an energy efficient design tries to get the highest visibility (ESI fc) with the lowest footcandles.

What is the same visibility? The ESI method equates the visibility of a task in the real environment to its visibility under reference lighting conditions (photometric sphere). The ESI method answers the question, "What is the level of illumination required inside the sphere (ESI fc) to provide the same visibility as the level of illumination in the real environment (raw fc)?" This is what is meant by the question, "What is the Equivalent Sphere Illumination (ESI)?"

How is visibility determined? The ability of the eye to see an object (visibility) depends on the contrast between the object and the background. Contrast is defined by the Blackwell contrast formula given on page 49. Certain animals show an imitative resemblance to their surroundings, thus camouflaging them from preditors. This is an example of inability to see because of lack of contrast. Visibility is also based on the size of the object and the length of time required to assimilate information about the object. An empirical evaluation of this information has been adopted by the IES and is known as the Standard Relative Contrast Sensitivity (RCS) Function of Luminance. The curve represents the eye's sensitivity to contrast. Visibility, then, is equal to the sensitivity to contrast multiplied by the contrast available.

$$\text{Visibility} = \text{RCS} \times \text{C}$$

where

RCS = Relative Contrast Sensitivity

C = Contrast

Notice that visibility is proportional to the contrast of the task. This means that under identical lighting conditions, different tasks will produce different visibilities. Hence one important factor in properly using the ESI method is defining the tasks to be performed, since different tasks will produce different ESI footcandle values. Most ESI calculations have in the past been based on the standard pencil task (#2 pencil on white paper, 25° viewing angle), but other tasks are now available and even more will be available in the future.

Remember that ESI is the level of illumination inside the photometric sphere that provides the same visibility as the level of illumination in the real environment. Mathematically this can be expressed from the previous equation as:

Contrast in sphere	x	Sensitivity to contrast in sphere	=	Contrast in real environment	x	Sensitivity to contrast in real environment

or:

$$C_o \times RCS_e = C \times RCS$$

where

C_o = Equivalent Contrast (calculated or measured)

C = Real Contrast (calculated or measured)

RCS is the sensitivity to contrast as a function of the task background luminance in the real environment.

RCS_e is the sensitivity to contrast as a function of the task background luminance in the photometric sphere.

Solving for RCS_e:

$$RCS_e = \frac{C}{C_o} \times RCS = CRF \times RCS$$

where

$$\frac{C}{C_o} = \text{CRF (Contrast Rendition Factor)}$$

Once RCS_e (equivalent sensitivity to contrast) is calculated, L_e (equivalent background luminance inside the sphere) needed to produce that sensitivity can be determined from the Standard RCS Function of Luminance.

$$RCS_e \rightarrow \text{Visibility (RCS) Curve or Table} \rightarrow L_e$$

The diffuse reflectance of the task background in the sphere, ρ_o, can be calculated or measured and is a constant for a given task.

The ESI is then calculated by

$$ESI = \frac{L_e}{\rho_o}$$

The mathematics to calculate ESI are quite simple and straightforward once the numbers are known. The calculated ESI can then be compared to a recommended level of Equivalent Sphere Illumination, E_s.

Fig. 1-15 gives a flow diagram of the method just described for determining the ESI of a task in a room. The CRF is calculated from VTP (Visual Task Photometer) measurements. The illuminance on the task, E_t, and the luminance of the task background, L_B, are measured. The L_B value is entered into the RCS curve to find an RCS for the task background luminance. The equivalent RCS (RCS_e) is found by multiplying the CRF by RCS. This takes into account the veiling reflections. The RCS_e is then entered into the RCS curve and an L_e is found. Dividing this equivalent luminance, L_e, by the diffuse reflectance characteristics of the task, ρ_o, gives Equivalent Sphere Illumination. Appendix B is an example problem of an ESI calculation.

A brief examination of the problem makes the calculation of ESI seem quite simple. What makes the method so complex that it requires the use of a computer? The problem is the determination of CRF, or more specifically, the task contrast in the real environment C (since C_o, the contrast in the sphere, is a constant for a given task).

$$\frac{C}{C_o} = \text{CRF (Contrast Rendition Factor)}$$

What is needed to calculate C? The value of C is arrived at by the Blackwell contrast formula:

$$C = \left| \frac{L_B - L_O}{L_B} \right|$$

However, the factors that affect the values of L_B and L_O are:

1. Room dimensions

2. Room surface reflectances

3. Luminaire layout

4. Luminaire candlepower distribution and polarization

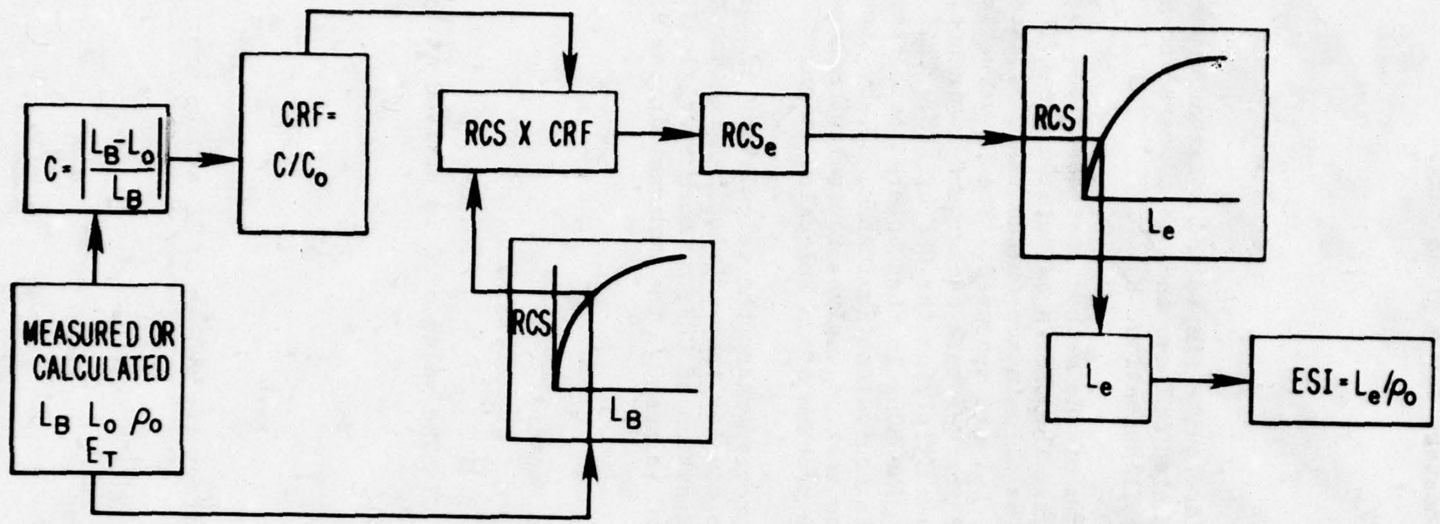

Figure 1-15 Flow Diagram for the Calculation of ESI

5. Physical characteristics of the task
6. Viewing angle
7. Test location
8. Viewing direction

It is actually the calculation of the object and background luminance that makes the procedure so complicated. The equations involved in calculating L_B and L_O are:

$$L_B = \Sigma[\beta_{(\theta,\psi)_B} \times E_{(\theta,\psi)_T}]$$

$$L_O = \Sigma[\beta_{(\theta,\psi)_O} \times E_{(\theta,\psi)_T}]$$

Since $\beta_{(\theta,\psi)_B}$ and $\beta_{(\theta,\psi)_O}$ (Bi-Directional Reflection Factor - see Section 1.1) are constants for a given task, the problem actually comes down to the calculation of illumination at a point. The illumination at a point is made up of two components: 1) direct and 2) interreflected illumination. As long as the luminaires can be divided into small areas, the direct component calculation simply involves the Inverse-Square Law and the Cosine Law of Illumination. Once the luminances of the room surfaces are determined, each surface can be treated as an emitter. That is, each surface becomes a source of light which could be divided into small areas so that the Inverse-Square Law and the Cosine Law of Illumination can be used to calculate the illumination at a point. This process can be used in determining the interreflected component. The calculation of the interreflected component involves the use of Radiant Flux Transfer. The computer is necessary to handle the volumes of information and data required to make these lengthy calculations.

1.4.2 Color

One aspect of visibility often ignored is color. Color is not a property of objects, but is a psychological response to the different wavelengths of radiant energy incident on the retina. It provides the human visual system with another dimension by which to judge the visual field.

Color has been the subject of studies for centuries. Such noted scholars as Newton, Brewster, Helmholtz, and Young studied the basic mechanisms of human color vision. This work produced the two basic theories of color - the Subtractive Color Mixing Theory and the Additive Color Mixing Theory.

The Subtractive Color Mixing Theory is used to describe color when working with pigments or dyes. Three primaries were found to exist - magenta, yellow and cyan. These primaries could be mixed to produce the seven colors of the spectrum. By mixing pairs of the subtractive primaries, the subtractive secondaries are formed - red, blue, and green. A mixture of all three

primaries produced black pigment. Subtractive Color Mixing is represented in Fig. 1-16.

The Additive Color Mixing Theory is used to describe energy produced by light. The three primaries of the Additive Color Mixing Theory are red, green, and blue. The secondaries, formed by pair combinations of the primaries are yellow, magenta, and cyan. The combination of all three primaries produces white light. This is shown in Fig. 1-17.

Selective absorption is the phenomenon by which objects produce their color. These two theories make it easier to understand selective absorption. For example, why does a green object appear green? If the object is illuminated with "white light" formed by mixing the three additive primaries (red, green, and blue), the object appears green due to the absorption of red, and blue light energy. Fig. 1-16 shows that green pigment is produced by a mixture of cyan and yellow. The cyan in the pigment absorbs its complimentary color red while the yellow absorbs its complimentary color blue, leaving only green light to be reflected (Fig. 1-18).

These two theories are used to explain color, but they are inadequate for specifying it. Three systems are in use today that classify and specify color. The Ostwald and Munsell systems are based on pigments, while the CIE Chromaticity system is based on the interaction of the human visual system, the light source, and the object.

The Ostwald system uses 24 distinct hues or colors to which are added a certain percentage of black and white pigment. The three dimensions used to describe color are the hue (color), the percent white, and the percent black. For example, a typical Ostwald notation might be 7LE where 7 is the hue scarlet, L is the % white content, and E is the % black content. Additional information on the Ostwald system can be found in the *IES Lighting Handbook*[1] on page 5-11.

The Munsell system is also three dimensional. Color is described by hue, value, and chroma. Hue is the name of a spectral color, value is a measure of the brilliance or amount of white, and chroma is a measure of the color purity. To specify a color under the Munsell system the hue, value/chroma are given. For example, 2.5G 5/6 is 2.5 green, a value of 5, and chroma of 6. A full set of color chips of the Munsell system can be obtained from the Munsell Color Foundation.

While using either of the pigment systems, it is necessary to have a particular light source so that the systems always produce the same perceived colors. The CIE Chromaticity system, on the other hand, can have any light source.

In the CIE system the human visual system is represented by three curves known as the CIE color-matching functions. By knowing the Spectral Power Distribution of the source and the reflectance distribution of the object under investigation, the perceived color can be determined. For each color-matching function, the source SPD is multiplied by the color reflectance, which is multiplied by the sensitivity of the receiver, the eye. The three stimuli thus produced are combined into two numbers which can be plotted on

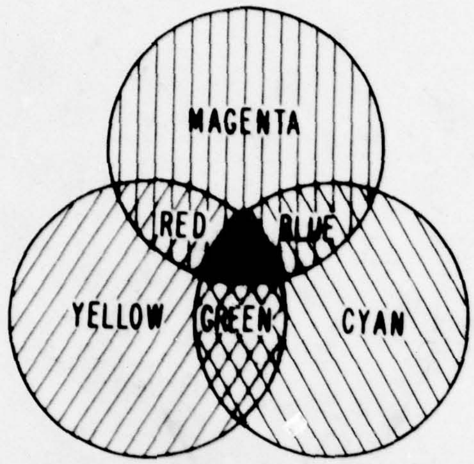

Figure 1-16 Subtractive Color Mixing

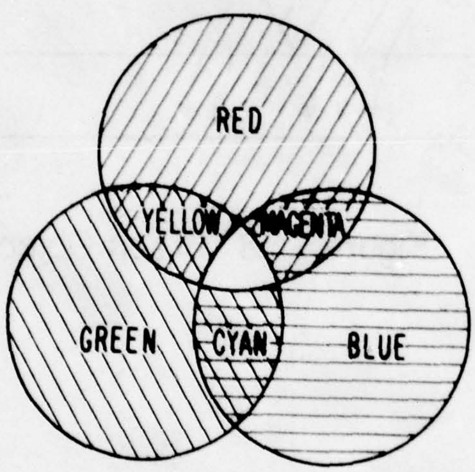

Figure 1-17 Additive Color Mixing

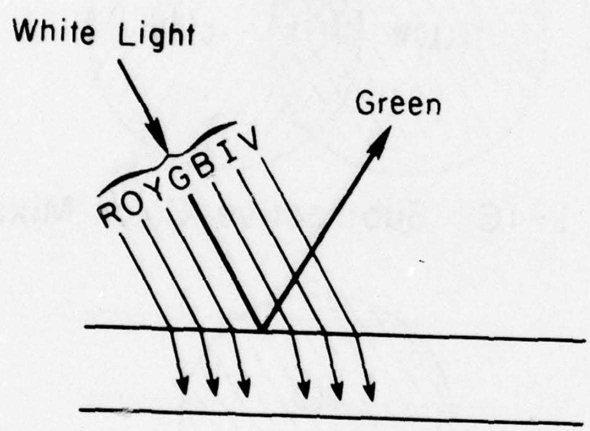

Figure 1-18 Green Object

the CIE Chromaticity Diagram. These chromaticity coordinates then are an expression of the perceived object color under the illuminant used.

The CIE Chromaticity system is very powerful in the specification and analysis of color. The reader is directed to the *IES Lighting Handbook*[1], page 5-4, or to "Principles of Color Technology" by Billmeyer and Saltzman for more details of the CIE Chromaticity system.

So far this section has covered color theory and color specification, but equally important is color psychology. Early man must have felt the psychological and emotional effects of the colors he perceived. The description of color psychology is tough but terms such as "warm and advancing as opposed to cool and receding," "stimulating as opposed to relaxing" or "neutral" are normally used to describe the emotions evoked by colors. Warm colors are usually red, red-orange, and orange. Shades of these colors are considered warmer than pure colors. Green and blue are considered cool, the tints of which are cooler than the pure colors. A neutral color might be yellow-green or gray.

Since color has such a psychological impact on the human, its use on interior surfaces becomes extremely critical. This manual is not to make interior designers out of those using it, but merely points out the fact that color is important. A good reference on how to use color is Inside Today's Home by Faulkner and Faulkner.

1.5 ARTIFICIAL ILLUMINATION DESIGN TECHNIQUES

There are many techniques in artificial illumination design. Basically, they are variations of a few techniques that fall into two classifications - Quantity and Quality.

1.5.1 Quantity Determination Methods

For many years only the quantity of illumination was determined. Although the quality of the illumination is considered today to be more important than the quantity, there are instances when the determination of the quantity will suffice. The basic technique in calculating illumination is the point-by-point method. Another useful method of determining the quantity of illumination is the Lumen Method.

Point-by-Point. The point-by-point method of determining the direct component of illumination is an application of the basic law of illumination, the inverse square law:

$$E_n = \frac{I}{D^2}\,\theta \qquad (1)$$

The law states that the illumination, E_n, at a point on a surface normal to the light ray is equal to the luminous intensity, I, of the source arriving at

the point divided by the square of the distance, D, between the source and point of measurement. This is shown in Fig. 1-19.

Although the inverse-square law is simple, a number of assumptions limit it. The most important assumption is that the source must qualify as a point source. If the maximum source dimension is one-fifth the distance to the point of calculation, the error will be less than 1%. Because a point source is required, it may be necessary to divide a large source into small sectors. This is valid only if the luminance of the source is constant from point-to-point at any viewing angle. Finally, asymmetrical distributions may cause error at particular points because interpolation of luminous intensity between planes given in published tables cannot be made reliably.

The inverse-square law equation gives the illumination on a plane perpendicular to the direction of the incident light. When the plane of interest is at an angle to the incident light (Fig. 1-20), the Cosine Law of Illumination must be applied. The equation then becomes

$$E_h = E_n \cos\theta \qquad (2)$$

where E_h is the illumination on a horizontal plane due to flux incident at an angle θ to the normal. Or replacing E_n in equation (2) with equation (1):

$$E_h = \frac{I_\theta}{D^2} \cos\theta \qquad (3)$$

If the illumination on a vertical plane is desired, the sine of the angle θ is used - Fig. 1-21.

If a number of calculations are to be made from an array of sources at the same height, H, the geometric relationship

$$D = \frac{H}{\cos\theta}$$

can be substituted into equation (3) to give the Cosine Cubed Law of Illumination:

$$E_h = \frac{I_\theta \cos^3\theta}{H^2}$$

In this form, only the direction of the intensity need be known, eliminating the calculation of the distance to the point of interest. A number of examples are given in Appendix C.

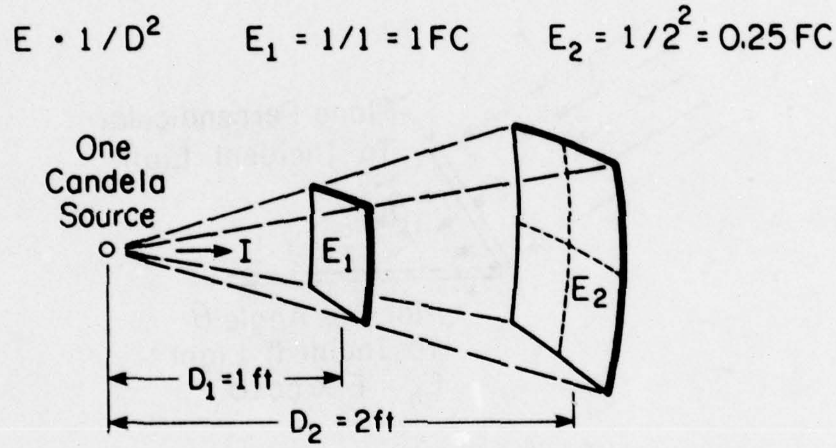

Figure 1-19 Inverse-Square Law of Illumination

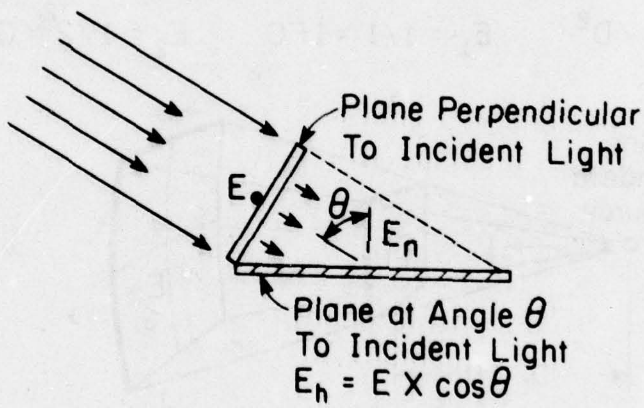

Figure 1-20 Cosine Law of Illumination

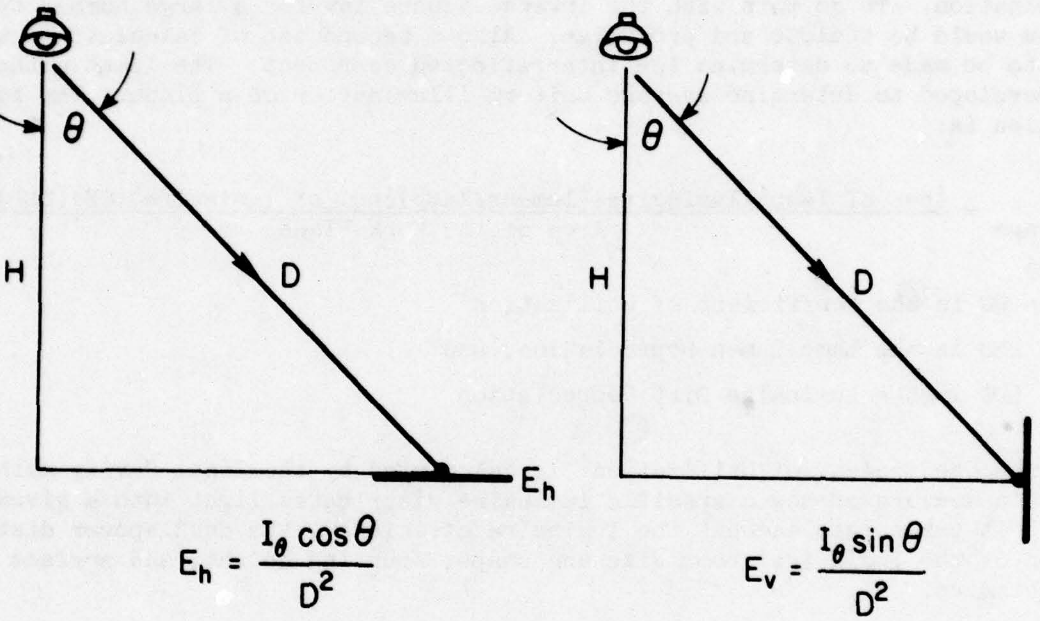

Figure 1-21 Illumination on a Vertical and Horizontal Plane

The inverse-square law and Cosine Law of Illumination are basic to almost every method of illumination design. Isofootcandle diagrams and tables of illumination values are such design methods. Only the direct component of illumination can be determined using the inverse-square law. Multiple interreflections from walls, ceiling, and floor may occur. A method of calculating the interreflected component is described in a report by the IES Committee on Lighting Design Practice[10].

Lumen Method. Often it is required to know or to design for average illumination. To do this with the inverse-square law for a large number of points would be tedious and expensive. Also a second set of calculations would have to be made to determine the interreflected component. The lumen method was developed to determine average uniform illumination on a plane. The basic equation is:

$$E_{\text{average}} = \frac{(\text{no. of lamps/luminaire})(\text{lumens/lamp})(\text{no. of luminaire})(\text{CU})(\text{LLD})(\text{LDD})}{\text{Area of the Work Plane}}$$

where CU is the Coefficient of Utilization

LLD is the Lamp Lumen Depreciation, and

LDD is the Luminaire Dirt Depreciation

The Coefficient of Utilization[1] is calculated by the Zonal Cavity method and is a measure of how a specific luminaire distributes light into a given room. It takes into account the luminaire efficiency, the candlepower distribution of the luminaire, room size and shape, mounting height, and surface reflectances.

Coefficients of Utilization for a particular luminaire are found in tables included as part of the photometrics of that luminaire. A CU table is shown in Appendix A. The tables are for a floor reflectance of 20% and a spacing to mounting height ratio of 0.40.

Fig. 1-22 is a room with the parameters used to determine the CU. The quantity known as the Cavity Ratio (CR) is defined

$$CR = \frac{2.5\ (\text{Area of the walls})}{(\text{Area of the work plane})}$$

Each of the cavities formed above has an associated Cavity Ratio:

$$\text{Ceiling Cavity Ratio (CCR)} = \frac{2.5\ h_{cc}\,(\text{perimeter of the walls})}{(\text{Area of the work plane})}$$

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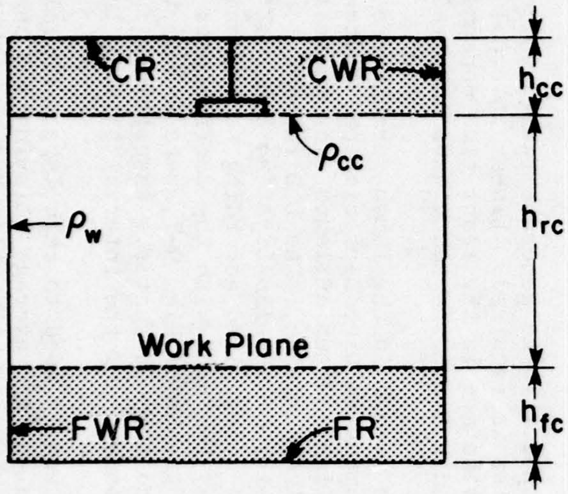
[10] "The Determination of Illumination at a Point in Interior Spaces," Committee on Lighting Design Practice of the IES, April 1973.



h_{cc} - Ceiling Cavity Height

h_{rc} - Room Cavity Height

h_{fc} - Floor Cavity Height

CWR - Ceiling Cavity Wall Reflectance

ρ_w - Room Cavity Wall Reflectance

FWR - Floor Cavity Wall Reflectance

CR - Ceiling Reflectance

FR - Floor Reflectance

ρ_{cc} - Effective Reflectance of Ceiling Cavity

ρ_{fc} - Effective Reflectance of Floor Cavity

Figure 1-22 Terminology Used in the Zonal Cavity Method

$$\text{Room Cavity Ratio (RCR)} = \frac{2.5\ h_{rc}(\text{perimeter of the walls})}{(\text{Area of the work plane})}$$

$$\text{Floor Cavity Ratio (RCR)} = \frac{2.5\ h_{fc}(\text{perimeter of the walls})}{(\text{Area of the work plane})}$$

The height of the ceiling cavity is the suspension length of the luminaires, while the floor cavity height is the distance from the floor to the work plane on which the average illumination is being calculated.

Referring back to the CU Table, to find a CU value, the effective ceiling cavity reflectance, ρ_{cc}, the wall reflectance, ρ_w, and an RCR are needed (the entire table is based on a 20% floor reflectance). If the suspension length is zero, then the effective ceiling cavity reflectance, ρ_{cc}, is equal to the actual ceiling reflectance. For suspension lengths other than zero, the ceiling cavity ratio (CCR) is calculated. Entering the table on pages 9-10 & 11 of the *IES Lighting Handbook*[1] with the ceiling reflectance CR, the ceiling cavity wall reflectance CWR and the ceiling cavity ratio CCR, an effective reflectance ρ_{cc} is found. The same procedure is used for an effective floor cavity reflectance ρ_{fc} when the work plane is any height off the floor.

With the effective ceiling cavity reflectance ρ_{cc}, the wall reflectance ρ_w, and the room cavity ratio RCR the CU is picked from the table. This CU value is based on a ρ_{fc} equal to 0.20. If the calculations have shown it to be something other than 20%, a correction factor must be applied to the CU. The table of correction factors is on page 9-32 of the *IES Lighting Handbook*[1] in Fig. 9-13.

Since it would be impossible to generate tables to cover all reflectances, interpolation of the tables is required. Linear interpolation is sufficient for this type of calculation and is the least time consuming. Refer to the example problems in Appendix D for the techniques involved.

Two other quantities needed in the lumen formula are the LLD (Lamp Lumen Depreciation) and LDD (Luminaire Dirt Depreciation) factors. These take into account the decrease in light output of lamps over their life and the accumulation of dirt on luminaire surfaces. The LLD factors for different lamps are found on pages 8-57 to 8-107 of the *IES Lighting Handbook*[1]. For the LDD factor, each luminaire is categorized according to its maintenance characteristics. This category may be found with the Coefficients of Utilization. Knowing the category the graphs of Fig. 9-7, page 9-6 of the *IES Lighting Handbook*[1] are used to find the LDD factor. Assumptions must be made as to the cleanliness of the environment and the interval between luminaire cleaning.

The Zonal Cavity method is used to calculate a CU value which is used in the lumen method to calculate the average illumination on the work plane. This average could be a number of highly lighted area while the remainder of

the room is dark. To assure the illumination is uniform (a necessary condition in the lumen method) the recommended spacing to mounting height ratio (S/MH) should not be exceeded. In addition, to prevent drop off of illumination near the walls the *IES Lighting Handbook*[1] recommends methods for spacings designed to compensate for any, pages 9-34 & 35.

A number of assumptions have been made in the Zonal Cavity method. The accuracy of the results is therefore limited. Also, it must be remembered that an average illumination is calculated. Use of the lumen method should be limited to noncritical uniform ambient lighting and to making a preliminary determination of the approximate number of luminaires needed. Where visibility of critical tasks is important, more sophisticated techniques should be used.

The reader is referred to IES Transaction LM-43[10] for other techniques for determining the level of illumination.

1.5.2 Quality Determination Methods

As can be seen it is relatively easy to predetermine the amount (quantity) of illumination on a point or surface. To determine the quality of illumination is much more complex. The theory behind the two approved IES methods for determining the visual quality of a lighting installation is discussed in Section 1.4.

An available program for predetermining VCP or ESI is Lumen II. The computational techniques involved in Lumen II are presented in the IES Journal[8,11]. The operation manual for Lumen II contains examples of how to use the program.

1.6 THE LUMINOUS ENVIRONMENT

Artificial lighting is an interaction of luminous energy, the room, and the visual task to permit an individual to perform a visual task in a given environment. So far, the source of luminous energy, lamp and luminaire, has been discussed as well as the relationship of the human observer to the task. The room is as important in artificial lighting as the task and luminaire.

There are seven characteristics of a room that have an impact on the lighting. They are:

1. Surface reflectances
2. Size
3. Shape
4. Windows

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[11] DiLaura, D. L., "On the Computation of Equivalent Sphere Illumination," Journal of the Illuminating Engineering Society, January 1975.

5. Maintenance
6. Temperature and
7. Furniture or equipment in the room

Windows and their effect are discussed in Section 2, while the effect of temperature is discussed in Section 1.7.

1.6.1 Surface Reflectances

The light that falls on any seeing tasks in a room comes from two sources - the luminaire itself and the surfaces of the room. The amount of direct light from the luminaires reaching the task is dependent on maintenance and temperature. The reflected component, however, is dependent on the surface reflectance, location, and size. Each surface in a room (the walls, the ceiling, and the floor) can have a different reflectance. The reflectance of each has a different effect on the reflected light.

Depending on the type of lighting system being used, the ceiling may be of major importance. With a totally direct lighting system the amount of light reflected off other surfaces that can reach the ceiling is small. The reflectance of the ceiling for a direct system is less important in making a contribution to the work surface. Fig. 1-23 shows the effect on Coefficient of Utilization for a direct and direct-indirect luminaire for a 30% change in ceiling reflectance. Often the luminance ratio between luminaires and ceiling is more critical than the interreflected illumination contribution. The higher the ceiling reflectance, whether a direct or indirect system is used, the lower the luminance ratios and the more comfortable the occupants will be.

The amount of light falling on the walls in a good lighting system should be of sufficient magnitude to provide field luminances and luminance ratios that are comfortable. Depending on the reflectance properties, the wall luminance and thus the interreflected component will change. Fig. 1-24 shows the effect on CU with a direct luminaire when the wall reflectance is increased by 20%. This shows that ideally all white walls would give the highest illumination level. The sterile environment of all white can cause occupant distress, and color is necessary to provide psychological relief. Any color has a reflectance less than white, though proper choice of colors will provide a pleasant, well-lighted environment.

Even if the architect and lighting designer provide light colored walls, the owner may reduce the efficiency of the system by installing dark furniture, pictures, blackboards, etc., that absorb light. If energy conservation is to be the responsibility of the design team, they must have a voice in the selection of the colors, furniture, and the placement of both.

The floor, depending on the particular tasks involved, can be important in providing reflected light. Fig. 9-13 of the *IES Lighting Handbook*[1], shows that the floor correction factors for 10% or 30% floor reflectances have little effect on the CU value. For tasks located on top of the work plane there is little effect. In this situation, the light has to be reflected off the floor, to the ceiling, and finally to the task. If the task is oriented on the bottom

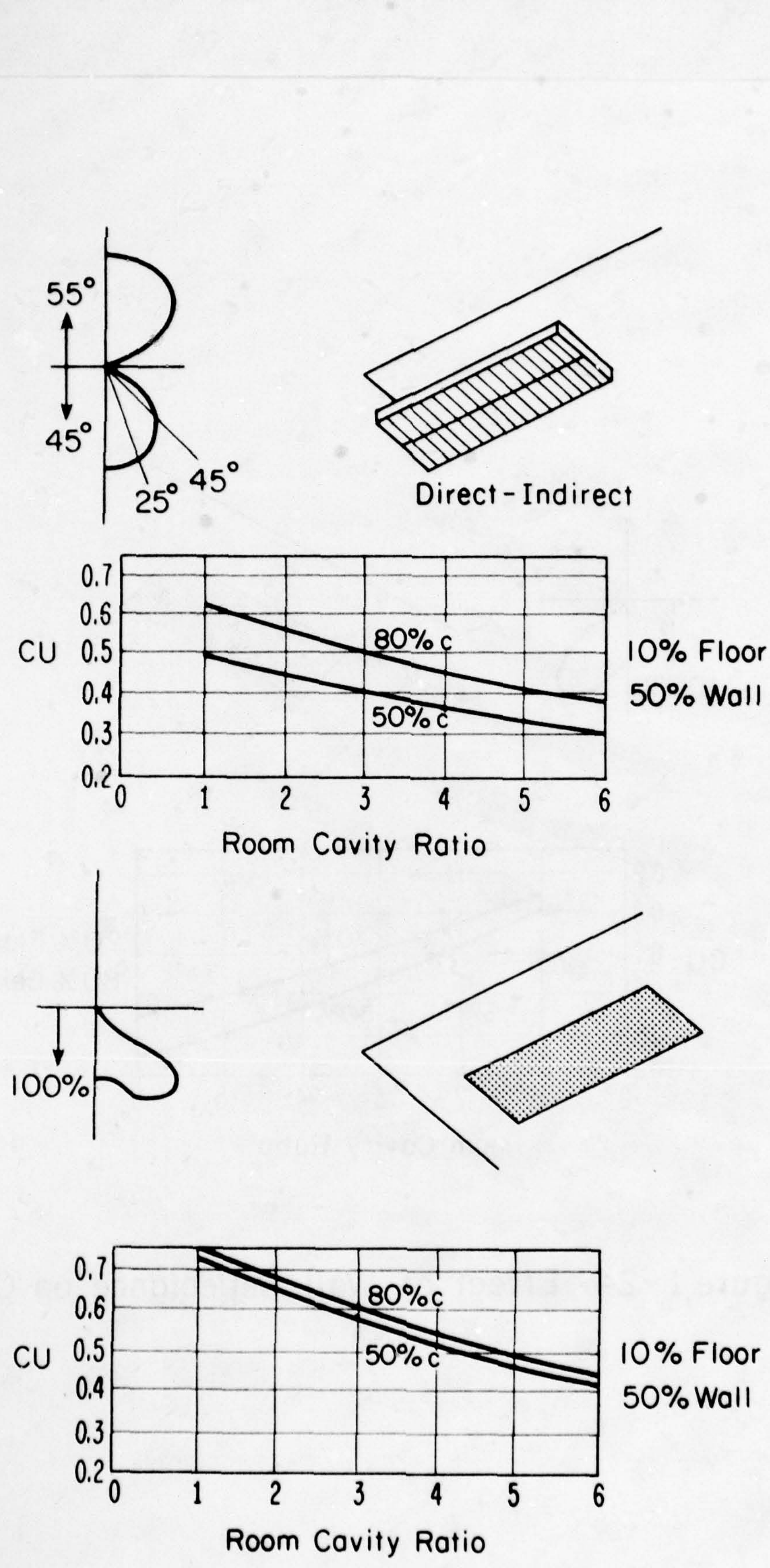

Figure 1-23 Effect of Ceiling Reflectance on CU

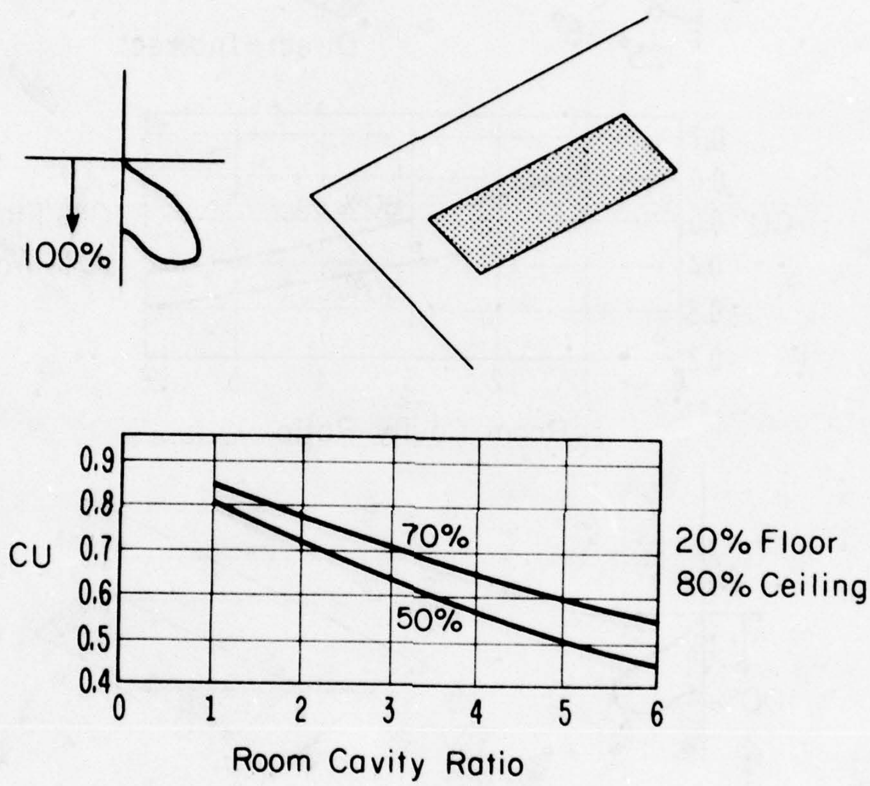

Figure 1-24 Effect of Wall Reflectance on CU

of the work plane, on the other hand, the floor reflectance becomes important. An example is hangars for repair work on airplanes. Many of the tasks are on the underside of wings or fuselage. With a low reflectance floor, supplementary lighting is required. Bringing the floor reflectance up from 20% to 80% eliminates the need for supplementary lighting.

The size and shape of the space affect the distribution of luminous flux in the space. To show the effect, the Coefficient of Utilization of the Zonal Cavity method will be compared for changes in geometry. A review of a number of luminaires (pages 9-12 through 9-30 of the *IES Lighting Handbook*[1]) shows that the CU decreases as the room cavity ratio (RCR) increases. Since RCR is a function of the room only, actual CU's need not be determined. For rectangular rooms with the same floor area and same room cavity height, a change in the proportions of the length and width does not affect the RCR. A change in height, however, increases the RCR. The higher the RCR, the lower the CU. This is logical because the increase in distance from the luminaire to the work plane decreases the illumination by virtue of the inverse-square law. A change in shape, from a rectangle to a circle with the same floor area, shows an interesting decrease in the room cavity ratio. A circular room has a higher CU value than a rectangular room of the same floor area, and thus a higher illumination level.

If the floor area is increased, while the room cavity height remains the same the RCR decreases. That is to say, large rooms can be lighted more efficiently.

1.6.2 Luminous Depreciation

One of the biggest factors affecting the performance of a lighting system is the deterioration of the components. The accumulation of dirt, lamp depreciation, and discoloration of lenses decrease light output. These enter into the Lumen Formula as the LLD and LDD. Other factors include luminaire surface depreciation, burnouts, and room surface dirt depreciation.

The design of a lighting system should be such that the required illumination is provided when the system is putting out the least amount of light. Since a decrease in efficiency does occur, this provides the occupants with at least the required illumination. The extent to which the system is overdesigned at the start is dependent on how well the maintenance requirements are identified, and how well a maintenance program is carried out once the system is installed. If dirt is allowed to accumulate, lamps are not replaced until they burn out, and discolored lenses are not replaced, the lighting system is going to require a larger initial investment to compensate for light loss. Fig. 16-16 of the *IES Lighting Handbook*[1] shows the light output losses and compares the losses using different maintenance schedules. There is approximately 13% more light at the lowest output point in schedule 4 than in schedule 1. Obviously a system following schedule 4 would have to put in 13% less equipment than the one following schedule 1.

The light output of lamps decreases as they get older. This is known as the lamp lumen depreciation. The values for different lamps are given on pages 8-57 to 8-107 of the *IES Lighting Handbook*[1]. The effect of lumen

depreciation can be reduced by planned replacement such as group relamping where all the lamps are replaced at some interval less than 100% rated life. Generally, group replacement of lamps is more economical than the spot relamping of individual burnouts. An analysis of the situation will determine the most economical method based on costs, desired illumination, and replacement of burnouts (those that burnout before the scheduled relamping). By using the following equations found on page 16-19 of the *IES Lighting Handbook*[1] the cost per socket for lamps and labor for a year can be found.

Individual replacement

$$\text{dollars/socket/year} = \frac{B}{R}\,(c+i)$$

Group replacement (early burnouts replaced)

$$\text{dollars/socket/year} = \frac{B}{A}\,(c+g+KL+Ki)$$

Group replacement (no replacement of early burnouts)

$$\text{dollars/socket/year} = \frac{B}{A}\,(c+g)$$

where B = burnings hours per year

R = rated average lamp life, years

A = burning time between replacements, hours

c = net cost of lamps, dollars

i = cost per lamp for replacing lamps individually, dollars

g = cost per lamp for replacing lamps in a group, dollars

K = proportion of lamps failing before group replacement (from lamp mortality curve Fig. 1-25)

L = net cost of replacement lamps, dollars

The variables of the equations can take on different values depending on historical information or the estimate of the engineer. The burning hours, B, can be found from the typical operation of the facility. For example, an office area would be in use for 2,340 hr/yr (9 hr/day X 5 days/wk X 52 wk/yr). The rated average lamp life, R, is found in manufacturers' catalogs. Currently a fluorescent lamp has an R of 22,000 hr. The net cost of lamps, c, depends on the quantity purchased. A fluorescent F40T12 lamp is about 93¢ per lamp. Records or time studies will determine the labor cost involved in individual replacement, i, and group replacement, g, of each lamp. With a fluorescent system, the replacement of individual lamps could cost $10. If all four lamps were replaced in a four lamp luminaire, the cost per lamp could drop. A possible figure would be one-fourth the individual replacement cost since only

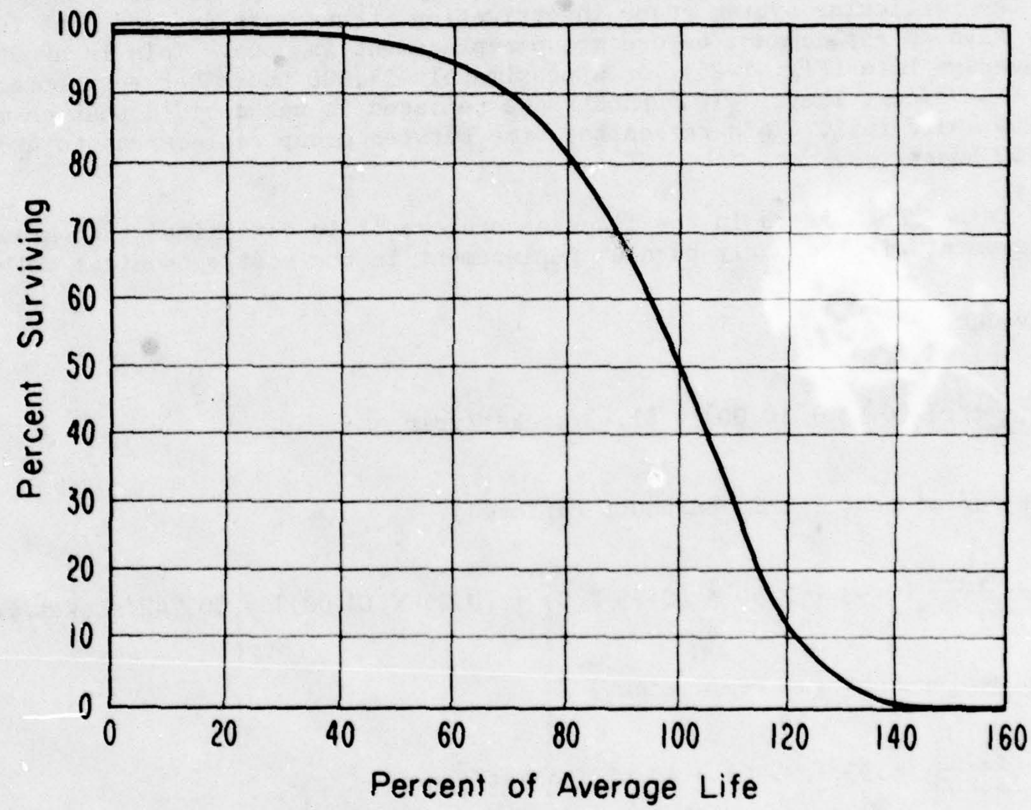

Figure 1-25 Lamp Mortality Curve

one set-up is made to change all four. In a program where early burnouts are replaced before the group relamping, either new lamps or lamps saved from a previous group relamping can be used to replace those that have burned out. The replacement lamp cost, L, can then be from the cost of a new lamp, c, to nothing. Typically spot replacement is done with used lamps and the cost, L, is zero.

The above factors depend, for the most part, on easily identifiable quantities. The burning time between replacements, A, and the proportion of lamps failing before group replacement, K, are dependent on the desired maintained illumination. For example, if early burnouts are replaced, the time between group replacement, A, can be longer than if they are not replaced. For the particular system under investigation it has been decided that 10% can fail with no replacement before group replacement is done. This is about 70% of average life (Fig. 1-25), or approximately 14,000 hours between replacement for fluorescent lamps. If burnouts are replaced it was decided that as many as 25% could fail. This raises the time between group replacement to about 18,700 hours.

Using the numbers in the discussion above it is determined that group replacement with no early burnout replacement is the most economical method.

Individual replacement

$$\frac{2,340}{22,000}(0.93 + 10.00) = \$1.63/\text{socket/year}$$

Group replacement (early burnouts replaced)

$$\frac{2,340}{18,700}(0.93 + 2.50 + (0.25 \times 0) + (0.25 \times 10.00)) = \$0.742/\text{socket/year}$$

Group replacement (no replacement)

$$\frac{2,340}{14,000}(0.93 + 2.50) = \$0.573/\text{socket/year}$$

The above analysis shows which method is least costly. There is no formula to determine the time between replacements, A, and the proportion failed before replacement, K. Various values, chosen for their effect on the illumination, should be tried to find the alternative with the least cost.*

Airborne dirt deposited on luminaire surfaces affect the light output and distribution. The environment, i.e., the amount and kind of dirt, determines the dirt depreciation. Also the luminaire design, lamp, and finish can determine how much of the dirt will eventually deposit on the luminaire. Ventilated designs tend to collect dirt less rapidly than those with closed tops. On the other hand completely closed units, if properly designed, exclude almost all dirt.

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*A computer program is available which will compute the effect on illumination levels and economic costs by various relamping and cleaning cycles.

While dirt can collect on luminaire surfaces, the surfaces themselves can also lose their ability to reflect or transmit light. Anodized and enameled reflective surfaces deteriorate. Environments that contain highly caustic materials cause surfaces to deteriorate faster. The use of plastic lenses has presented the added problem of yellowing. Depending on the light source, luminaire temperature, and type of plastic, the period of time before the transmitting properties of the lens begin to change varies.

Luminaire cleaning at the time of lamp replacement brings the system to optimum efficiency. By relamping and cleaning at the same time, labor costs can be cut. Lenses should be replaced whenever they yellow, although nothing can be done about luminaire surfaces that have deteriorated except to replace the entire luminaire.

It seems that if the luminaires are cleaned and relamped occasionally, the major light loss factors will have been taken care of. Since high room surface reflectances have been shown to be a requirement for good system efficiency, any decrease in room surface reflectances will increase light loss. Depending on the environment, room surfaces should be washed periodically and painted when the reflectance has dropped significantly. Maintenance should be performed more frequently where a larger percentage of light is reflected by these surfaces. It should be noted that sometimes surfaces appreciate, i.e., the reflectance rises. Bleaching out of paint, curtains, or other materials, as well as, light-colored dust can cause the appreciation of surface reflectances.

1.6.3 Objects in Room

Most preliminary design is done assuming that the space is entirely empty. When furniture and equipment are placed in a room, the distribution of the light can change radically. Furniture that is light in color with a matte finish will prevent absorption of light and glare. Shadows that occur from equipment shielding light can be prevented by properly locating equipment with respect to the lighting system. As task lighting equipment, (i.e., equipment that is located near the task and oriented properly) is improved, the problem with shadowing will be minimized.

1.7 THERMAL AND ACOUSTICAL IMPACT ON THE ENVIRONMENT

Besides putting light into the space, luminaires introduce thermal and acoustical changes to the space. Most of the time, lighting designers ignore the impact of lighting equipment on the environment. To provide an integrated environment, all factors must be considered.

1.7.1 Thermal

Electrical equipment (including lighting) produces 3.41 BTU of heat per watt of power. The transfer of this heat energy occurs by radiation, conduction, and convection. This heat can be used in the winter to supplement the heat requirements, but must be removed when cooling is required. This

load on the air conditioning system is taken care of by increasing the capacity of the cooling equipment. It has been suggested that energy can be saved by turning off lights in existing installations resulting in a savings in energy used for lighting, as well as, that used for cooling. In most systems this may be true, however, in the case of systems using electric resistance heaters to maintain the design air temperature the reduction in air temperature causes the reheat coils to cycle on increasing the air temperature to its design level. Therefore, each system must be analyzed carefully to determine the impact of lighting on the mechanical system. The coordination of lighting and mechanical design is essential to the optimization of both.

Selection of efficient sources and luminaires, proper room surface reflectances, and the use of task-ambient lighting will reduce the lighting system wattage. Any heat produced must still be considered in the design of the mechanical system.

If the heat from the lighting system can be utilized rather than being dumped or wasted, the energy consumed by the heating system can be reduced to the degree to which the lighting provides heat to the space. The heat from the lighting system must be redistributed to areas where it is needed. A number of schemes have been proposed (Fig. 16-10, page 16-6 of the *IES Lighting Handbook*[1]). The most common means of using the heat produced by the lighting is the air-handling luminaire. They are designed to be used as supply diffusers or return air vents. As the return air passes through the luminaire, it picks up the heat generated by the luminaire and returns it to the mechanical system. Since the air has been heated, the amount of heat added to the redistributed air during a heating cycle can be reduced. The heat that is added to the cooling load will result in a more efficient system since the heat is added before the coils rather than into the room. Furthermore it will reduce the amount of air that has to be supplied to the room.

A secondary benefit of the air-handling luminaire is the potential for increased light output. Section 1.2 shows that a variation in ambient temperature can affect the light output of a fluorescent lamp. The buildup of heat can decrease the light output. The air-handling luminaire, if properly designed, can reduce the ambient air temperature in the luminaire resulting in more efficient operation and utilization of energy. Proper luminaire housing design and mounting details conduct some of the heat away, but not as much as the air-handling luminaire. A comparison[12] of the air-handling luminaire to the conventional luminaire shows in general that the increase in luminaire efficiency for the air-handling luminaire is sufficient to pay for the added cost. As energy becomes more expensive and scarce every BTU will have to be used efficiently, which means a more thorough investigation of the interaction of the systems.

1.7.2 Acoustical

In the past few years, the concern about the acoutstical environment has

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[12]Finn, J. F., "Efficient Application of Lighting Energy - A Luminaire Air Heat-Transfer Evaluation," Lighting Design & Application, January 1976.

increased as technology has brought about a noisy environment. The lighting system has also added to the noise pollution that surrounds us.

Lighting equipment, especially gaseous discharge lamps which require inductance ballasts, is a noise source. Incandescent lamps if dimmed, may emit an audible ringing which can be eliminated by adding a choke coil in the power supply line. Fluorescent ballasts have undergone numerous improvements, including a reduction in noise level. They are available for very quiet installations, "A" rated, to those where a high noise level is acceptable, "F" rated. Fluorescent equipment manufactured for indoor applications should be equipped with an "A" sound rated ballast. Even with an "A" rated ballast, the fluorescent luminaire will emit some acoustical energy. A poorly constructed luminaire or a poor mechanical connection of the ballast to the luminaire will cause a speaker effect. If the luminaire is well constructed and the noise still presents a problem, the ballast can be located outside of the critical area. This can be expensive and create a voltage drop which needs to be investigated.

Unlike fluorescent ballasts, the other gaseous discharge ballasts have been used almost exclusively outdoors where a high noise level could be tolerated. With the energy crisis, more indoor applications of HID have arisen. There is no standard industry sound rating for HID ballasts. The noise characteristics of HID ballasts used inside should be evaluated by the designer before they are specified. As with fluorescents, the luminaire construction can have as much effect on the sound level as the ballast alone.

A possible solution to the noise problem is the use of a solid state ballast which has been under development for some years. Besides their many other advantages, the solid state ballast operates with almost no noise.

The noise generated by a luminaire is not the only effect the lighting system can have on the acoustical environment. Most lighting equipment is installed in the ceiling where acoustical tile absorbs sound. The hard surfaces of the luminaire on the other hand reflect sound. In an open office where partial height partitions are used for privacy, an improperly located luminaire reflects speech from one cubical to the other negating the purpose of the partition.

Office buildings are commonly designed with dropped acoustical ceilings. Walls extend up to the suspended ceiling only, leaving a completely open plenum. An opening in the luminaires allows sound to travel through one luminaire into the plenum and out another luminaire. This problem is quite common in modern office buildings.

1.8 ENERGY CONSIDERATIONS

1.8.1 General

Lighting has been one of the key rallying points for mandatory standards to conserve energy consumption. To put the role of lighting as it relates to energy conservation into perspective, let's look at the impact of lighting on the total energy resource consumption in the U.S. The goal of energy

conservation should be to reduce the consumption of energy resources.

Currently, 80% of the resources used in this country are Fossil Fuels (Coal, Oil and Natural Gas)[13]. The most critical fuels in terms of estimated reserves are oil and natural gas. Of the total resources consumed, approximately 25% are used to generate electricity. Twenty percent of that 25% ends up as lighting. That means that approximately 5% of the total energy resources consumed in this country end up in the form of lighting. Approximately 9% of the 25% used to generate electricity involves oil and natural gas. That is, only 3% of the total energy resources used to generate electricity involves critical fuels. With these facts, the question must be asked - Why is lighting a target for energy conservation? Lighting is "visible." Secondly, in terms of the final end user, the lighting represents 30 to 50% of the operating cost of a building. Lighting energy conservation is important in terms of the total resource reserves and in terms of operating cost for the building owner. As utility rates continue to increase, the impact of lighting on operating cost will become painfully apparent. Make no mistake, there is a lot of wasteful lighting. Qualified lighting engineers have known for years, that high levels of uniform lighting throughout a space are wasteful. For example, the *IES Lighting Handbook*[1] recommends 100 footcandles (Fig. 9-80, page 9-81) at the task for general office work involving "hard pencil or poor paper reading fair reproductions ..." The problem facing the engineer is the task definition and location. Since neither of these design parameters are known during a typical design process[14], the designer blankets the entire space with 100 footcandles. This uniform approach is not recommended by the IES but resulted from a lack of communication and understanding of fundamentals on the part of the engineer and architect. The *IES Lighting Handbook*[1] (footnote, Fig. 9-80, page 9-81) states "... illumination levels shown in the table are intended to be minimum on the task ..."

1.8.2 IES 12 Recommendations

In 1972, the IES prepared 12 recommendations[15] for better utilization of energy in lighting design without sacrificing quality. The recommendations cover the operation, maintenance, and selection of lighting equipment. The recommendations apply to new construction as well as renovations or retrofit (upgrade).

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[13]Helms, R. N., "Lighting and Energy Conservation - What is Reasonable?," Electrical Consultant, May 1975.

[14]Helms, R. N., "Lighting Design without Analysis: The Consulting Engineer's Dilemma," Proceedings - The Basis for Effective Management of Lighting Energy Symposium, Federal Energy Administration, October 29 & 30, 1975, Washington, D.C.

[15]Ringgold, P., "In the Interest of Illumination," Lighting Design & Application, November 1972, pp. 1a-6a.

IES 12 Recommendations[15,16]

1. Design lighting for expected activity (light for seeing tasks with less light in surrounding nonworking areas).
2. Design with more effective luminaires and fenestration (use systems analysis based on life cycle).
3. Use efficient light sources (higher lumen per watt output).
4. Use more efficient luminaires.
5. Use thermal controlled luminaires.
6. Use lighter finish on ceilings, walls, floor and furnishings.
7. Use efficient incandescent lamps.
8. Turn off lights when not needed.
9. Control window brightness.
10. Utilize daylighting as practicable.
11. Keep lighting equipment clean and in good working condition.
12. Post instructions covering operation and maintenance.

1. Expected Activity - A design approach that uses lower ambient levels with higher task levels will produce an energy efficient system. The task location must be known in order to supply the appropriate lighting level at the task location.
2. More Effective Luminaires and Fenestration - Luminaires and fenestration systems should be as efficient as possible without adversely affecting comfort (VCP) and visibility (ESI).
3. Efficient Light Sources - Selection should be based not only on the efficacy (lumens/watt) but also on the life, cost, and color rendition. Color should carry as much weight as the other factors since color has a direct bearing on the psychological behavior of people which affects productivity and mood.
4. More Efficient Luminaires - Efficiency includes the utilization of energy in the space as well as cleaning and relamping convenience.
5. Thermal Control - Make use of the heat produced by the lighting equipment.
6. Reflecting Surfaces - The absorption of light in a space due to low reflectance values will reduce the efficiency of the lighting system resulting in an increase in wattage.
7. Efficient Incandescent Lamps - If incandescent lamps must be used, the higher wattage lamps will be slightly more efficient than lower wattage lamps.

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[16]Kaufman, J., "Optimizing the Uses of Energy for Lighting," Lighting Design & Application, October 1973.

8. Lights Off When Not Needed - Switching off lights when not in use will result in energy savings and a reduction in operating costs. The effectiveness of the energy reduction is a function of the flexibility of the control systems.

9. Window Brightness - Excessive glare of windows on the line of sight will affect comfort and visibility which may reduce performance.

10. Daylighting - The effectiveness of daylight is dependent on the combined daylight/artificial lighting system. Unless the control system is properly designed, energy reduction is questionable.

11. Maintenance - Good maintenance will require fewer luminaires by increasing the utilization of the light entering space. Maintenance should include not only spot relamping but also room surface cleaning, painting, luminaire cleaning, and group relamping.

12. Operating and Maintenance Instructions - The design of sophisticated lighting systems and controls for energy conservation will be wasteful if the building user does not know how to properly use and maintain the system. The designer should provide instructions on how to use the system.

1.8.3 ASHRAE 90-75

The ASHRAE Standard 90-75 was an outgrowth of an NBS (National Bureau of Standards) document which was prepared for the NCSBCS (National Conference of States on Building Codes and Standards). The NBS document was entitled "Design and Evaluation Criteria for Energy Conservation in New Buildings" and was published in early 1974. NCSBCS asked ASHRAE to prepare a standard on energy conservation in new buildings which would be based on the NBS document. In the Spring of 1974, IES was asked by ASHRAE to prepare Chapter 9 on lighting. A revised format of Chapter 9 was prepared and sent to ASHRAE in May 1974. The May 1974 revised version was different from the earlier version in that it established a procedure for determining a "Lighting Power Budget." After numerous revisions, two public review periods, and five meetings of the IES Task Committee on Energy Budgeting Procedures, a Lighting Power Budget Determination Procedure (Chapter 9) was approved in July 1975 by the Board of Directors of IES. In late 1975, the ASHRAE Standard - 90P (P-preliminary) was approved and became ASHRAE Standard 90-75. The concept of power budgeting to set a limit on power consumption is new and innovative. The procedure is based on task lighting and the use of efficient light sources and equipment. The procedure needs to be continually evaluated and revised as the public gains valuable experience in applying the power budget procedure. The power budget procedure has been approved as a Transaction of the IES[17] and is available from IES. A series of three Energy Management documents are now available.

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[17]Documents available from: Illuminating Engineering Society, 345 East 47th St., New York, NY 10017. All three documents: Members $6.00, Non-members $12.00.

EMS-1 IES Recommended Lighting Power Budget Determination Procedure

EMS-2 An Interim Report Relating the Lighting Design Procedure to Effective Energy Utilization

EMS-3 Example of the Use of the "IES Recommended Lighting Power Budget Determination Procedure"

It is imperative that the designer realize that this is a budgeting procedure that sets a limit on the amount of power that can be designed into the lighting system in a new building. It is not a lighting design procedure, it is an analysis procedure. The budget represents an upper limit. To achieve meaningful energy conservation, the designer should strive to use less power without sacrificing the quality of the system. An example of the use of the power budgeting procedure can be found in Appendix E. For a more complete example of the Power Budget Procedure, the designer is referred to the IES document[17] EMS-3.

The use of the ESI method (Section 1.4.1) of analyzing visual performance can result in energy conservation. Energy reductions can be achieved by producing high visibility (ESI) with lower illumination levels ("raw" footcandles). Since "raw" footcandles are directly related to energy consumption (watts), energy savings can be realized by controlling veiling reflections. Veiling reflections reduce visibility as expressed by lower ESI values. The *IES Lighting Handbook*[1] gives some guidance for "Reducing Veiling Reflections" (page 3-32). Reductions in lighting levels ("raw" footcandles) that result in a reduction in visibility (ESI) will result in a "false" energy savings. A reduction in visibility will result in a reduction in performance and productivity. A reduction in performance and productivity may result in an increase in time spent in a space to complete a job which may result in an overall increase in energy consumption.

1.9 EXTERIOR LIGHTING CRITERIA

Exterior lighting must be well planned to optimize the use of exterior facilities while minimizing energy consumption. Security and safety are the primary functional needs associated with Naval facilities. Roadway, area, and floodlighting are the three design techniques available to satisfy these functional needs.

Once a functional need has been established, the designer must select the most efficient equipment to maximize the utilization of the energy while minimizing the power consumption. The quality of illumination will have a direct bearing on the safety, efficiency, and appearance of the system. The quality is dependent upon glare control, transient adaptation, color, and aesthetics.

Glare and transient adaptation will affect the safe movement of pedestrians and vehicles. Good glare control will minimize wasted spill light which will increase the overall efficiency of the system by increasing the utilization of energy. Direct glare (Section 1.4.1) is the major problem encountered in most exterior lighting. It causes annoyance, discomfort, and/or a loss in visiblity. The sensation of glare is a result of the luminance of

a source being much higher than the surround luminance to which the eye is adapted. The emphasis on direct glare has been brought to the forefront in the past 2 years because of the awareness on the part of people of light pollution in the environment. Transient adaptation relates to the effect created by changing the direction of view and exposing the visual system to variations in the luminance patterns in the field of view. For example, as one drives down a roadway, his visual system will adapt to an ambient level of luminance. Excessively bright light sources, such as oncoming headlights and streetlights, momentarily affect adaptation state. The greater the luminance difference (luminance ratios) between the source and the surrounding area, the slower the rate at which the visual system will return to its original adaptation level. It is during this re-adaptation process, that a loss in visibility is experienced which could result in an accident. A reduction in glare, hence luminance ratios, will result in a reduction in the amount of clutter and confusion reaching the visual system. This decrease in clutter and confusion will create a more pleasant, safer environment for pedestrians and vehicles.

Color is also important in the exterior environment since it influences the mood and behavior of people and thus their performance. High performance is essential to the security of facilities as well as safety.

Exterior lighting can be classified into static or movable systems. The static system is one in which the luminaire is not adjustable on its support and is positioned towards a single fixed point. Most roadway and pedestrian luminaires would be classified as static systems. The movable system is one in which the equipment can be aimed at different points. Floodlighting equipment with adjustable support mechanisms would be classified as movable.

Light sources are described in detail in Section 1.2. A brief summary of light sources as they apply to exterior lighting is included in this section.

1. Incandescent lamps should be avoided for exterior applications because of their low efficiency and short life. Incandescent lamps create high operating and maintenance costs.
2. Fluorescent lamps should be avoided for exterior applications because of their sensitivity to temperature and the poor quality of optical control. Enclosed and gasketed luminaires may maintain a sufficiently high ambient temperature to allow for operation under low temperatures, however, that same enclosure that holds the heat in the unit during the cold also holds the heat in during warm weather which causes a drop in lumen output of the lamps. Because of the physical size of the light source, optical control will be poor resulting in lower utilization characteristics.
3. Low pressure sodium lamps produce monochromatic yellow light which turns all colors except yellow, gray, brown, or black. The lamp alone has a very high efficiency. However, when the source is combined with a ballast and luminaire the overall efficiency of the system is low. Because of the physical size of the source, the optical control is poor resulting in low utilization characteristics[18]. Because of its overall lower system

[18]McGowen, T. K., "HPS and LPS - a Primer," Lighting Design & Application, December 1974, pp. 19-23.

efficiency and poor color rendition, low pressure sodium applications should be analyzed very carefully.

4. Mercury vapor lamps require a phosphor coating if color rendition is to be acceptable. The phosphor coated lamp represents a large source which means that optical control is poor and utilization decreases. The mercury vapor lamp also has a relatively low efficacy which makes it the third choice for exterior applications.

5. Metal halide and high pressure sodium lamps have relatively small light emitting elements (arc tubes) which allow for good optical control. Each of the two sources has high lamp efficacy and good system efficiency. This makes these two sources the first and second choices for exterior applications. The metal halide has better overall color balance and is preferred where color is important. The high pressure sodium has a dominant orange appearance that may be objectionable for some applications.

1.9.1 Roadway Lighting

General. The roadways in and around Naval Facilities may require lighting to facilitate the safe movement of personnel from one area to another. Roadway lighting is especially important where mixed modes of movement converge, such as vehicular/pedestrian and automobile/service vehicle. These roadway systems should use low-glare luminaires that produce very little intensity between 70° and 90° from nadir and no intensity 90° or above. A reduction in intensity at these high angles (70° to 90°) will reduce light pollution, minimize spill light, and optimize the use of energy by placing the light where it is needed. High angle intensity (70° and up) does little or nothing for producing illumination on the roadway surface.

The current roadway lighting standard[19] uses horizontal illumination and uniformity of illumination as the design criteria for roadway lighting. Both factors are deficient in terms of what the visual system actually sees. This is less than desirable but is currently the only procedure available to the designer. He should be aware of the deficiencies but can go ahead and use the standard until a new one becomes available.

The human visual system does not see the luminous energy coming <u>to</u> a surface (illumination), it sees the energy coming <u>from</u> a surface (luminance). A luminance design procedure is much more complex and requires information on the reflectance properties of the roadway surface. However, with the aid of the computer, the problem is not as impossible as one might be led to believe. Uniformity of illumination is also meaningless when talking about the uniform appearance of the pavement. The uniformity of the pavement is dependent upon the amount of light reflected towards the eyes (luminance) from various points on the surface. The pavement luminance is equal to the Bi-Directional Reflection Factor (Section 1.1) times the horizontal illumination.

$L = \beta_{(\theta,\phi)} E_h$ L - Luminance of the pavement surface

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[19] American National Standard Practice for Roadway Lighting, D12.1-1972, American National Standards Institute, 1430 Broadway, New York, NY.

$\beta_{(\theta,\psi)}$ - Bi-Directional Reflection Factor

E_h - Illumination on a Horizontal Surface

Assume $E_h = 1.0$ fc.

if $\beta_{(\theta,\psi)_X} = 0.0567$ for point X on the road, then

$L_X = 0.0567 \times 1.0 = 0.06$ fL

if $\beta_{(\theta,\psi)_Y} = 0.9409$ for point Y on the road

$L_Y = 0.9409 \times 1.0 = 0.94$ fL

This represents almost a 16 to 1 uniformity ratio in terms of luminance (what the eye sees) for a 1 to 1 uniformity ratio of illumination. Another misleading concept in the ANSI-IES Standard[19] is the "Cutoff" classification for roadway luminaires. The ANSI-IES "Cutoff" classification allows for a large amount of intensity to exist above 70°, as a matter of fact it will allow intensity to occur at and above 90°. The "Cutoff" classification can result in light pollution, wasted energy, and excessive glare. A standard roadway luminaire photometric data sheet can be seen in Appendix F. The photometric data sheet contains an isocandela diagram, isofootcandle curve, utilization curve, descriptive information, and a summation of "Flux values." An examination of the "Flux values" will demonstrate the energy wasteful characteristics of this type of luminaire. The "Flux values" represent the luminous flux (lumens) distributed within a given zone. The zones are divided into the downward hemisphere (House Side - DW HS and Street Side - DW SS) and upper hemisphere (House Side - UP HS and Street Side - UP SS). The luminaire is assumed to be placed inside a sphere. All of the luminous flux that is directed into the lower hemisphere, 0° to 90°, is summed to represent the downward component. While all luminous flux that is directed into the upper hemisphere, 90° to 180°, is summed to represent the upward component. The flux values for the luminaire in Appendix F are:

Flux Values %	
DW SS	63.6
UP SS	1.2
DW HS	14.5
UP HS	.7
	80.0%

This luminaire has an efficiency of 80%. This means that 80% of the total

bare lamp lumens actually get out of the luminaire or 20% of the bare lamp lumens are lost or absorbed inside the luminaire. Combining the upward and downward components for the same luminaire:

Flux Values %	
Downward	78.1
Upward	1.9
	80.0%

At first glance, this may look quite good. But what good is the 1.9% upward component? Will it ever reach the roadway surface? The 78.1% downward component looks good. But is it real? That 78.1% includes luminous flux from 0° to 90°. What percentage of that luminous flux is at or above 70°? How efficient is intensity from 70° to 90° in illuminating a roadway surface? A high percentage of intensity from 70° to 90° will create direct glare and is energy wasted in terms of the ANSI-IES Standard criterion of horizontal illumination.

This type of an analysis of data should be carried out when investigating any type of static lighting system used for roadway or area lighting. Once a luminaire has been evaluated and selected, the design procedure is quite simple and straight forward.

Design Procedure. The design procedure and terminology of roadway lighting is covered in the ANSI-IES Roadway Lighting Standard[19], and the *IES Lighting Handbook*[1] (pages 9-71 though 9-73). The design procedure uses a lumen formula to determine the spacing of the luminaires to produce a desired average maintained level of illumination.

$$\text{Spacing} = \frac{\text{Lamp Lumens X Utilization Factor X Light Loss Factors}}{\text{Illumination Required X Roadway Width}}$$

A sample roadway lighting calculation is given in Appendix F.

1.9.2 Area Lighting

Area lighting may be required at Naval Facilities to provide security lighting and for the safe movement of personnel. Area lighting can increase security by increasing visibility and thus reduce crimes against Navy property. The safety aspects of area lighting not only include crimes against personnel but also a reduction in accidents.

The use of movable or aimable systems for area lighting is quite common. The approach has been to place floodlighting units on poles and aim them out to flood an area with light. One must remember that as a unit is tilted up and out, the internal parts of the luminaire and light source are exposed to the direct line-of-sight. This approach may be initially less expensive but it creates glare, excessive spill, and wasteful energy utilization. Because of the effect on transient adaptation, the visibility may be reduced to a point

that is detrimental to both security and safety.

The trend in area lighting has been to move away from movable or aimable systems to static systems used in roadway light. The use of low-glare high efficiency systems is recommended for area light. The same principles and procedures outlined in Section 1.9.1 apply to area lighting.

1.9.3 Building Lighting

Building lighting can increase the aesthetic appearance of a selected structure as well as acting as security lighting. Lighting of the exterior surface of the building can reduce crimes such as burglary and theft by making the exterior surfaces more visible to security personnel.

The primary concern in building floodlighting is to minimize glare and maximize the distribution of illumination on the building surface. The required level of illumination is a function of the reflective properties of the building, the ambient surrounding luminances, and the aesthetic appearance desired. Building floodlighting is the terminology used to describe ground mounted or pole mounted equipment which is set back some distance from the building. Building lighting can also be achieved by equipment mounted directly to the structure.

Building floodlight lighting design can use a lumen method (pages 9-68 to 9-69 of the *IES Lighting Handbook*[1]) or point-by-point procedure to calculate the illumination level on the building. The lumen method is used to determine the number of floodlights to give a required level of illumination. Once the layout has been determined, the uniformity must be checked using a point-by-point method.

1.10 COSTS

1.10.1 Cost Factors

As always the final decision on which lighting system to install, should be based on the cost. These costs should not only include the first cost of the installation, but also the operating and maintenance costs. With the rise in energy cost and inflation in all sectors of the economy an inexpensive system (low initial cost) could cost the owner many times more to operate and maintain.

Identifying all the cost factors for economic analysis is the hardest part of the analysis. Fig. 16-26, page 16-19, from the *IES Lighting Handbook*[1], indicates a number of factors that have been found to affect the lighting system cost. The "footcandles maintained" of the table should be replaced with "ESI maintained" for areas in which the visibility requirements have been defined and analyzed. As more data on the relationship of productivity to lighting is gathered and a dollar amount is attached to productivity, the economic analysis will be based on tangible figures rather than a recommended footcandle or ESI level. The relationship of productivity to the quality and quantity of illumination is the subject of current research.

The statement "better and energy efficient lighting will cost more initially" is not applicable to every situation with certainty. It is probably true, but each situation should be subjected to the economic test. So many factors are involved that the decision on which system to use should not be made on initial cost - either the lowest or highest - alone. A number of examples[20,21,22,23] of lighting system economics can be found in the literature.

One of the costs that is very important to the analysis of the least cost alternative is the electrical or utility rate. Depending on whether an average cost per kilowatt hour or the actual cost per kilowatt hour is used will greatly affect the outcome of the analysis. Utility rates are based on a number of different schemes, such as block rates (which may have an increasing or decreasing charge with increased usage) or demand rates (which are based on the required capacity of the utility to supply power). As can be seen, the utility rate can be a complex maze of numbers from which the designer has to determine the rate which he will enter into his analysis. It is, therefore, mandatory that the designer determine accurately these costs.

A comparison of the cost of different lighting systems leaves out many other factors involved in the total building equation. The lighting system affects the mechanical system because of luminaire heat, and heat gains and losses through windows. The floor areas, floor to ceiling heights, and floor to floor heights affect building volume which again affects the mechanical and lighting systems. The discussion[24] of the total building energy picture shows that changes in lighting have little effect on the total energy used, but does greatly affect the productivity of workers.

1.10.2 Analysis Methods

There are a number of methods of economic analysis by which to review the different choices. The method chosen depends on the purpose and use to which

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[20] Griffith, J. W., "Resource Optimization and Economic Planning," Lighting Design & Application, September 1973, pp. 23-27.

[21] Mangold, S. A., "Lighting Economics Based on Proper Maintenance," Lighting Design & Application, August 1974, pp. 6-11.

[22] Finn, J. F., "A Lighting System Cost Comparison," Lighting Design & Application, January 1975, pp. 26-27.

[23] Lange, A. W., "New Design and Specification Techniques Cut Energy Costs and Offer Optimum Efficiency," Lighting Design & Application, February 1976, pp. 10-13.

[24] Dorsey, R. T., "Cost-Benefit Analysis Applied to Lighting in the Energy Equation," Lighting Design & Application, July 1975, pp. 36-38.

the analysis is put as well as the factors of interest in the analysis. The four types of analysis used in the Navy are: the payback period, the internal rate of return, the present value, and the savings investment ratio. A detailed description of these methods and how they are used by Navy personnel can be found in NAVFAC P-442. The particular cost elements intrinsic to the Navy are identified and explained. Although Section 1.10.1 did not address itself to inflationary factors, NAVFAC P-442 requires their inclusion. With the tremendous increases in the cost of energy recently, this factor is critical to the analysis of the operating costs. Operating cost is an on-going cost that will have to be paid down the road and will continue to escalate. Appendix D shows an example of the economic comparison of lighting systems.

1.11 STATE-OF-THE-ART AND ON-GOING RESEARCH

1.11.1 State-of-the-Art

The development of design techniques that evaluate visibility in terms of visual performance has brought about rapid changes in the state-of-the-art in lighting. The impact of the ESI method on lighting technology has been quite important. The designer finally has a handle on one of the major factors that affects how well one can see task detail, hence perform the task. The designer can now evaluate one of the quality aspects of lighting design. With the development of a computer program[25] the designer can predetermine the ESI levels produced in a luminous environment. He can truly evaluate a lighting system in terms of visibility. An ESI instrument[26] has been constructed and tested that allows one to measure the ESI values in a space. The theory and procedure for developing a second ESI instrument[27] was presented in a paper at the 1976 Annual Conference of the IES. Mr. Dave DiLaura (Smith, Hinchman, and Grylls, Detroit, Michigan) has actually constructed and demonstrated an inexpensive, lightweight, portable adaptor that when attached to a high precision, cosine-corrected footcandle meter will allow for the direct determination of ESI. Therefore, concern over the inability to measure ESI can seemingly be put aside. As the ESI method gains in acceptance, additional instruments and techniques for quantifying and evaluating ESI will be developed. BRDF's have been measured and are available for at least seven additional tasks. Additional tasks are being studied and will be measured in the very near future. Studies[28] are being conducted on the sensitivity of the ESI system to various changes such as different layouts, different luminaires, different spacing ratios, and different tasks.

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[25]Lumen II, a program developed by Dave DiLaura, Smith, Hinchman and Grylls, Detroit, MI.

[26]Ngai, Zeller & Griffith, "The ESI Meter - Theory and Practical Embodiment," Journal of the IES, October 1975, pp. 58-65.

[27]Otto, F. B., "A Meter to Measure ESI Footcandles," a paper presented at the 1976 IES Annual Technical Convention, Cleveland, Ohio.

[28]Lewin, I., "An ESI Study for Different Tasks," a paper presented at the 1976 IES Annual Technical Convention, Cleveland, Ohio.

Dr. Blackwell has developed refinements to the original CIE Report 19[29]. The refinements and expansion of the ESI methodology will appear in a Second Report of the CIE Committee TC-3.1. The report, which is entitled "Implementation Procedures for Evaluating Visual Performance Aspects of Lighting" will be released in mid-1977. The essence of the report was covered in a paper[30] presented at the FEA (Federal Energy Administration) Lighting Symposium in Washington, October 29 and 30, 1975. The expanded method described by Blackwell[30] leads to the calculation of Relative Performance, RP, as a function of reference illumination for different values of $\tilde{C}$, α, V, e, and VLM where

- $\tilde{C}$ - Equivalent contrast which is the contrast of the visibility reference task that has the same visibility as the actual task
- α - Is a measure of the difficulty of ocular search and scan, and off-axis information processing
- V - Is the proportion of the visual component in a task being performed. If $V = 1$, the task being performed is completely visual
- e - Error penalty which is a weighting coefficient for errors
- VLM - Visibility Level Multiplier, which accounts for differences in contrast sensitivity for different individuals of the working population. The justification or need for higher or lower levels of reference illumination levels, E_{ref}, can be demonstrated in terms of the five variables (listed above) which influence task performance

"Values of RP ...produced by a change in the level of reference illumination, should prove very useful in connection with cost benefit studies of lighting applications[30]."

This expanded procedure that expresses visibility in terms of Relative Performance can be combined with cost benefit analysis[31] to give a more complete indication of trade-offs in terms of energy conservation, productivity,

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[29]"Recommended Method for Evaluating Visual Performance Aspects of Lighting," CIE Report 19, prepared by Committee E-1.4.2 on Visual Performance, available through Mr. Louis Barbrow, Secretary USNC-CIE, National Bureau of Standards, Washington, D.C. 20234.

[30]Blackwell, H. R., "Energy Conservation by Selective Lighting Standards Graded in Terms of Task and Observer Characteristics," Proceedings - The Basis for Effective Management of Lighting Energy Symposium, Federal Energy Administration, Washington, D.C.

[31]Dorsey, D. T. and Blackwell, R. H., "A Performance-Oriented Approach to Lighting Specifications," <u>Lighting Design & Application</u>, Feb. 1975, pp. 13-27.

and profits. "... You'll not use the new CIE system without a significant increase in the money expended on technological services by the engineers who design the lighting[30]." The design engineer will not only spend additional time, but he must have a greater understanding of the new system to evaluate the five variables.

The current computer techniques used for evaluating ESI are analysis procedures. That is, the designer must investigate different combinations of luminaires and layouts to determine which system gives the best visibility for the dollars budgeted to the project. If a criterion level of ESI is specified he must also investigate different design combinations to find a system that will meet that criterion. A true design procedure would involve specifying a given ESI level at preselected task locations and have the computer determine the optimum combination of luminaires and layout to meet that criterion. This type of an optimization procedure was first described by Ngai[32,33]. Because of the complexity of optimization, progress in development of the procedure has been slow. There has been considerable discussion of optimization programs but to date no one has made any information public. The same can be said for synthesis programs. A synthesis program would bring together all aspects of the environment by optimizing the artificial lighting, daylighting, and thermal considerations in terms of cost benefits. This type of "super" - program may become a reality in the future but at this time computer technology (memory size) and man's understanding of the complex interactions are not at that level of sophistication.

1.11.2 On-Going Research Needs

On-going research must continue in the development of application procedures for the new CIE system[30]. There is a need to expand an upgrade data and design techniques in daylighting design. More must be learned about the psychological and physiological impact of lighting on the luminous environment and man. Direct glare evaluation systems for exterior lighting must be improved. The VCP Method as it applies to point sources such as HID equipment being used in the interior environment must be investigated. To complete the design procedure outlined in CIE Report 19, research must be continued to evaluate the TAF (Transient Adaptation Factor) and the DGF (Discomfort Glare Factor). Once the research is completed on TAF and DGF, application procedures must be established to incorporate the data into the evaluation procedure.

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[32]Ngai, P. Y., "Veiling Reflections and the Design of the Optimal Intensity Distribution of a Luminaire in Terms of Visual Performance Potential," Journal of the IES, Oct. 1974, pp. 53-59.

[33]Ngai, P. Y. and Helms, R. N., "Optimization - A Synthetic Approach to Lighting Design," Journal of the IES, July 1975, pp. 286-291.

II. DAYLIGHTING DESIGN

This section takes an unbiased, objective look at the impact of daylighting on the human occupants, luminous environment, and energy conservation. Daylighting is dealt with by first analyzing daylighting and then establishing design techniques. The analysis is in terms of the three primary aspects of daylighting: 1) exterior environment, 2) interior environment, and 3) interface medium - the window. The design establishes design parameters and techniques.

2.1 ANALYSIS OF DAYLIGHTING

The primary difficulty in daylighting is the variability of daylight with respect to the time of day and year, with respect to location (i.e., with geographical latitude), and with respect to environmental conditions. These variations in the quality and quantity of daylight (exterior environment) result in variations in the interior environment.

2.1.1 Exterior Environment

The exterior environment produces and influences the daylight that becomes the source of light for interior daylighting calculations. The constantly changing exterior environment is the key factor in the analysis of daylight. The three sources of light are the sun, sky, and ground.

Sun. The sun is the only known source of heat and light for the earth. It has a diameter which is more than 100 times that of the earth and is at a distance of approximately 93 million miles from earth. The radiant energy or solar radiation received from the sun is transmitted in the form of short waves including ultraviolet, visible, and infrared energy. The solar radiation is the most important source of heat which is produced by the absorption of most of the radiant energy including light.

Only 50 to 60% of the radiant energy reaching the outer limits of the earth's atmosphere actually reaches the earth's surface. The percentage of energy reaching the earth varies with latitude, season, and cloud cover. The losses in radiant energy are due to selective scattering, diffuse reflection, and absorption in the atmosphere. Scattering and reflection account for approximately 70% of the loss while the remaining loss is due to absorption by water vapor.

The rotation of the earth around its polar axis causes daily changes, and the rotation of the earth around the sun causes the seasonal changes. The Equinoxes represent the times when the sun's noon rays are directly vertical at the equator. There are two Equinoxes. One occurring in the Spring (March 21 - northern hemisphere - NH) is called the Vernal Equinox. The second occurring in the Fall (September 23 - NH) is called the Autumnal Equinox.

The solstices represent the times when the sun's noon rays are directly vertical at latitude 23-1/2°. The summer solstice occurs on June 22 (NH) when the sun is directly overhead at latitude 23-1/2° north or at the Tropic of Cancer. The winter solstice occurs on December 22 (NH) when the sun is directly overhead at latitude 23-1/2° south or at the Tropic of Capricorn.

The position of the sun at any given instant of time is expressed in terms of two angles. Altitude or solar altitude is the vertical angle (or elevation) of the sun above the horizontal plane. Azimuth or solar azimuth is an angle measure in the horizontal plane. The horizontal angle is measured from due south to the vertical plane through the sun (Fig. 2-1).

Sky. Small obscuring particles (such as dust) and water vapor act to diffuse the radiant energy as it passes through the atmosphere. This scattering and diffusion results in what is referred to as sky luminance. The belt of maximum radiant energy moves back and forth across the equator as the seasons change and from east to west as the earth rotates. The luminance of the sky forms a vault or dome of nonuniform luminance. Sky luminance is evaluated in terms of overcast sky or clear sky luminance.

Overcast sky luminance varies as a function of location, time, density of cloud cover, and uniformity of cloud cover. The luminance pattern is not uniform and will have a luminance about 2-1/2 to 3 times greater at zenith (overhead) than on the horizon.

Clear sky luminance varies as a function of the location of the sun and the amount of atmospheric haze or dust. The luminance of a clear sky is greater near the horizon than at zenith except in the vicinity of the sun where sky luminance increases.

Ground. Light reflected from the ground is a function of the reflective properties of the ground cover. The effectiveness of ground light is also dependent on the orientation (exposure to direct sun) of the window, obstructions between sun-ground and/or ground-window, and the height of the window above the ground.

Obstacles. Obstacles in the exterior environment may obscure contributions or increase reflected light from any one or more of the sources of light. Obstacles would include adjacent buildings or structures, and landscape. High landscape may obscure contributions from the ground, sun, and/or sky. The blocking effect of high landscape such as deciduous trees may vary from season to season. Lower landscape or ground cover may obscure contributions from the ground and may also be seasonal depending on the type of landscaping material.

2.1.2 Interior Environment

The daylight entering a space must be analyzed in terms of the quantity and quality of the light. Daylight may be sufficient in quantity to reduce artificial lighting level and result in false energy conservation if the quality of the light is not analyzed. A poor quality of daylight may result in discomfort and a loss in visibility which may cause a decrease in human

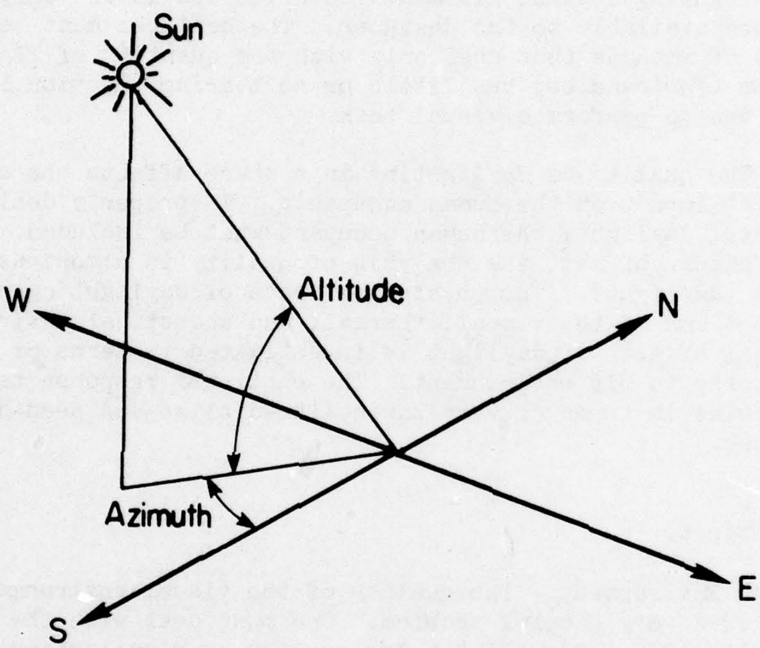

Figure 2-1 Altitude and Azimuth

performance and productivity. This loss in performance and productivity may result in an increased use of the space which may result in additional energy consumption.

Quantity. The footcandle is the unit associated with the quantity of daylight produced in a space, i.e., illumination. An illumination criterion is used in most methods of daylighting design because of the availability of instruments to measure footcandles and because of the relative ease in calculating illumination. The illumination levels may vary throughout the space at any given time depending on the number, location, orientation of windows, season, and exterior conditions. Because of the limited advances in numerical methods for daylighting design, illumination criterion is the only technique in the literature available to the designer. The designer must be aware of the limitations of methods that deal only with the quantity of light. That is, illumination (footcandles) has little or no bearing (Section 1.4.1) on the ability of man to perform a visual task.

Quality. The quality of daylighting in a space affects the physical and psychological impact on the human occupants. To properly deal with the quality aspects of daylight, the human occupant must be included. Because of the complex nature of man, the analysis of quality is almost as variable as the stimulus (daylight). The physical effects of daylighting can be investigated in terms of the visual, thermal, and acoustical environment. The psychological effect of daylight is investigated in terms of man's subjective response to his environment. The emotional response to daylight by man is looked at in terms of very basic like-dislike and need-don't need modes of response. .

(1) Physical Effects

(a) Visual Environment. The quality of the visual environment in terms of daylighting is a very complex problem. One must deal with the response of the human visual system to daylight. The quality of visual stimulus is dependent on many factors. This text deals with the three most important factors that affect quality, (i) glare, (ii) luminance ratios, and (iii) color.

(i) Glare: Glare can be defined as any excessively bright source of light within the visual field that creates discomfort and/or a loss in visibility. In laymans terms, discomfort is associated with pain, fatigue, strain, or increased tension. Loss of visibility is as the term implies, a complete or partial loss in the ability to see the task or object of interest. As a glare source moves closer to the line of sight, both discomfort and loss of visibility increase as an exponential function. For example, as the bright lights of an oncoming automobile approach the driver's line-of-sight, the effect on visibility and comfort will become greater. Therefore, glare is a function of the source, location, intensity, surrounding luminance, and direction of view. If the occupant is involved in "heads-up" (Section 1.4.1) tasks, direct glare will be the phenomenon of concern while occupants involved in "heads-down" (Section 1.4.1) tasks will be influenced by reflected glare or veiling reflections.

If the window is serving one of its primary psychological and emotional functions, that is, visual relief, it will be on the line-of-sight which will compound the problems of direct glare. The direct glare, from a source on the line-of-sight, may cause discomfort depending on the differences in luminance between the window and the interior environment. The greater the luminance difference or luminance ratio the greater the discomfort. The loss in visibility due to direct glare will be due to transient adaptation. Transient adaptation is a measure of the adaptation state of the visual system as the eye moves about the nonuniform environment. It takes time for the visual system to adapt to the variation in luminances within the luminous environment. Relative to daylight, the primary concern would be re-adaptation to the lower luminance of a visual task or object in the environment after subjecting the visual system to the potentially high luminance of the window. Adaptation from light to dark situations is referred to as dark adaptation. The luminance values in most interior environments would not be thought of as "dark". However, relative to the potentially high levels of luminance of the window, the luminance difference could vary from a ratio of 1 to 1 to more than 10,000 to 1. Fortunately, this adaptation for most interior environments involves the cone receptors which have a much quicker recovery time than the rods. The time it takes to re-adapt to the interior luminances is a function of the luminance difference between the window and the visual task, the length of exposure to the window luminance, the magnitude of the window luminance, and the size or visual angle subtended by the window. Re-adaptation time will increase with an increase in luminance difference, exposure, window luminance, and a decrease in window size. The time it takes to re-adapt will result in a temporary loss in the ability to see. Most occupants will compensate for this loss in visibility but sacrificing speed or accuracy. Loss in speed and/or accuracy will result in a reduction in performance, hence productivity. Although these losses may be small for a single glance at an excessively bright window, the accumulated losses over an 8-hour day could be significant. When evaluating energy reduction by replacing artificial light by daylight, one must look at the potential increase in work time and energy consumed to compensate for the possible loss in productivity due to direct glare, transient adaptation, and re-adaptation.

Reflected glare can result from the reflection of the image of the window off a specular surface (Section 1.3.1). As per Section 1.4.1, the problem of reflected glare involves source location and orientation of the task. Care in analyzing the location of the offending zone (Section 1.4.1) and proper orientation of tasks relative to windows will result in little or no problems with reflected glare.

Veiling reflections result in a loss in visibility due to a reduction in contrast (Section 1.4.1). Because of the strong unidirectional (unilateral placement) quality of most windows, the relationship between source and task location can be optimized. If the guidelines in Section 1.4 are followed, daylighting can result in increased visibility or higher ESI values. The daylight modification of Lumen II can be used to study the visibility (ESI) of various tasks under different task-window orientations. A study of the veiling reflection effects created by daylight is outlined in Appendix G.

(ii) Luminance Ratios: Luminance ratio is a ratio of luminance of a task to the luminance of the area surrounding the task. In daylighting, the

primary concern with regards to luminance ratios is between the luminance of the window and its immediate surrounding area of walls and/or mullions and frame. The visual system experiences increasing discomfort as the ratio between the window luminance and the surrounding area increases. Page 11-7 of the 4th Edition of the *IES Lighting Handbook*[34] indicates that the maximum luminance ratio anywhere in the visual field should not exceed 40 to 1. Page 11-3 of the 5th Edition of the *IES Lighting Handbook*[1] states that "for the best results the highest acceptable luminance of any significant surface in the visual field should not be greater than 5 times the luminance of the task." The 40 to 1 luminance ratio has been deleted from the latest edition. The author interprets the 40 to 1 luminance ratio to apply to the ratio between the window luminance and the surrounding area for an occupant who is casually looking around a space and not involved in looking back to a critical visual task. If the occupant is working on a critical visual task and looks up from that task, he should not be exposed to a luminance ratio greater than 5 to 1. If the ratio exceeds 5 to 1, a loss in visibility will occur as described in Section (i) - Glare.

(iii) Color: Color is important in terms of the psychological response to color (Section 1.4.2) as well as the color rendering characteristics. Object color is seen by a phenomenon known as selective absorption. That is object color is dependent on the pigment characteristics and the spectral distribution characteristics of the light source.

The spectral distribution characteristics of daylight[35] are made up of the direct sunlight and the diffuse light from the sky. In general, the diffuse sky creates more short-wavelength energy than the direct sunlight. The ratio of direct sunlight to diffuse sky light varies as a function of the solar altitude and azimuth, latitude, atmospheric density and transmission. The thicker the atmosphere the greater the effect on short wavelength transmission through the atmosphere.

The spectral distribution characteristics of daylight may also be modified due to transmission through different types of glass. Color rendering effects of daylight can be a complex matter. Since the spectral distribution of daylight plus the window can vary over quite a range, one must be careful to examine colors under the appropriate conditions. Since, most artificial light sources used for interior applications have vastly different spectral energy distribution characteristics than sunlight, one must be extremely careful when selecting colors to be used under the combined artificial/daylight luminous environment.

(b) Thermal Environment. The thermal aspects of the interior environment as affected by the window are dealt with in detail in Section 2.1.3. In general, the window affects the thermal environment in terms of heat transfer

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[34] *IES Lighting Handbook*, 4th Edition, Illuminating Engineering Society, 1966.

[35] Kimball, H. H., "Records of Total Solar Radiation Intensity and Their Relation to Daylight Intensity," Transaction of IES, May 1925, pp. 477-497.

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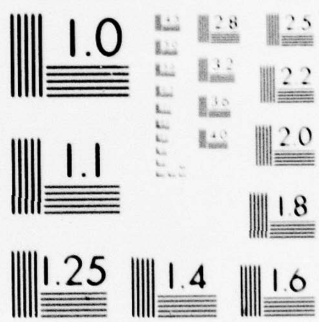

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between the interior and exterior environments and in terms of heat exchange and distribution within the interior environment.

(c) Acoustical Environment. The effect of the window on the acoustical environment will be dealt with in detail in Section 2.1.3. In general, the window affects the acoustical environment in terms of sound transmission through openings around the glass or through the glass. Secondary noise production within the environment can be generated due to improper fittings resulting in vibration or rattle. Also, smooth hard surfaces such as glass can reflect sound which may add to the ambient noise level.

(2) Psychological and Emotional

Psychological and emotional aspects of daylighting have not been specifically investigated. Preliminary studies[36] have been done on the psychological effects of light on man in terms of artificial light. This type of research needs to be extended to include the effects of daylight on attitude, well-being, and motivation. The basic question becomes, should the space have windows or should the space be windowless? The problem is more than simply balancing physical aspects of quality (visual, thermal, acoustic) against artificial lighting to produce energy conservation. One must be concerned with the way that daylight affects the user's spatial perception and human behavior. If daylighting or the absence of daylighting has an adverse effect on attitude and motivation it can have a detrimental effect on performance and productivity. Loss in performance and productivity may result in increased use of energy.

What are the effects of a windowless environment? The Architectural Research Laboratory of the University of Michigan conducted a study in 1962 of windowless classrooms[37] on the learning process. The test involved two elementary schools of the same type of construction. Mann Elementary School was used as the control situation with windows. Hoover Elementary was modified to be windowless for 1 year and a follow-up of 1 year with windows was included. Both elementary schools included kindergarten through third grade. Performance testing of the children in the windowless classroom indicated no effect on the learning process when compared to the students in the control school.

This type of study on windowless vs. window environments needs to be extended. In most cases where windows exist, occupants find that excessive direct sun and glare result in the use of a covering or shielding system which turns the space into a windowless environment. A covered window seems to be less disturbing than a truly windowless room, since the occupant knows that

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[36]Flynn, J. E., "The Psychology of Light: Series 1," <u>Electrical Consultant</u>, December 1972 - July 1973.

[37]"The Effect of Windowless Classrooms on Elementary School Children," published by the Architectural Research Laboratory, Department of Architecture, University of Michigan, 1965.

the windows are there if he wants to see outside.

The psychological and emotional impact of the window or the absence of the window needs to be investigated to determine the effect of these factors on performance, productivity, attitude, behavior, and motivation.

2.1.3 Fenestration

The interface between the exterior environment and the interior environment is the fenestration. The fenestration or openings are analyzed in terms of their application. The term "window" applies to all openings in the sidewalls or sidelight, while the term "toplight" applies to all systems utilizing an opening in the ceiling-roof plane which provides overhead light. This section concentrates on the analysis of physical characteristics of the most common interface material - glass. Some important characteristics of plastics are described as they apply to the interface for toplight.

Terminology and Units.

1. Transparent Glass (clear glass, vision glass) - a material that transmits light without any apparent change in direction or color. Objects can be seen clearly through the material in either direction.
2. Translucent - a material that transmits light but diffuses the light as it passes through. Objects cannot be seen clearly through the material.
3. Opaque - a material that will not transmit light.
4. Reflective Glass - a glass material that is coated on the outside with a transparent metallic oxide coating. During the daytime, when viewed from the inside the material appears transparent, and when viewed from the outside it appears to be opaque and acts as a mirror surface. The reverse is true at night.
5. Tinted Glass - glass that contains additives which change the color, appearance, and reduce transmission.
6. U-Coefficient of Heat Transmission (U-Value) - is the number of British Thermal Units per hour (BTUH) that pass through 1 square foot of interface material when the temperature difference between interior air and exterior air is $1^{o}F$ for a steady rate of heat flow.
7. Conductivity, k - is the number of BTUH that pass through 1 square foot of interface material 1 inch thick when the temperature difference (ΔT) between interior and exterior is $1^{o}F$ ($\Delta T = 1^{o}F$) for a steady rate of heat flow.
8. Conductance, C - same as conductivity except for a specific thickness (x) or a thickness other than 1 inch. ($C = k/x$).
9. Thermal Resistance, R - is the reciprocal of conductivity ($R = 1/k$) and is the number of hours required for 1 BTU to flow through the interface material of k, conductivity. For thicknesses other than 1 inch expressed as Conductance, C, the Thermal Resistance would be (x/k).

10. Air-Space Conductance, a - is the rate of heat flow (BTUH) between the bounding surfaces through 1 square foot of area for $\Delta T = 1°F$. It is affected by orientation and the Emissivity, E, of the bounding surfaces.

11. Emissivity, E - is the effective thermal absorption of the bounding surfaces of the air space.

12. Surface Film Conductance, f - is dependent on the speed at which the air strikes the interface material. It is the rate of heat flow (BTUH) through 1 square foot at $\Delta T = 1°F$ due to air motion across the surface; outside, $f_o = 4.0$ BTUH/ft^2/°F for a 7.5 mph wind, inside, $f_i =$ 1.46 BTUH/ft^2/°F.

13. Infiltration - movement of air between interior and exterior environments due to cracks around window. The airflow is usually from cracks on the windward side to cracks on the leeward side.

14. Thermal Pressure - is the difference (ΔT) between interior (t_i) and exterior (t_o) temperature.

15. Shading Coefficient (SC) - is a ratio of the solar heat gain of a sheet of glass to the solar heat gain of the "reference glass". The reference glass is double-strength sheet glass with $\tau = 0.86$, $\rho = 0.08$, $\alpha = 0.06$. Shading coefficient can be calculated as a ratio of the solar heat gain coefficient (F) of a sheet of glass to the "F" value for the reference glass. For single glass $F = \tau + \frac{U\alpha}{ho}$ for reference glass $F = 0.87$. Therefore $SC = \frac{\text{F of glass}}{0.87}$.

16. Greenhouse Effect - trapping of solar radiation by the conversion of absorbed radiation by surfaces within a room into long wavelength radiation. Most glass is opaque to long wavelength radiation beyond 3 microns.

17. Solar Optical Properties - transmittance (τ), reflectance (ρ), and absorptance (α). The total solar radiation striking a surface must equal the sum of the transmitted, reflected outward, and absorbed energy (Fig. 2-2).

$$\tau + \rho + \alpha = 1.00$$

The magnitude of each of the three optical properties is a function of the thickness of the glass, physical properties of the glass, surface properties (coatings or film), and the angle of incidence, θ.

Physical Characteristics of the Material.

Single Glass
- Clear
- Tinted
- Reflective

Double or Insulating Glass
- Clear
- Tinted
- Reflective

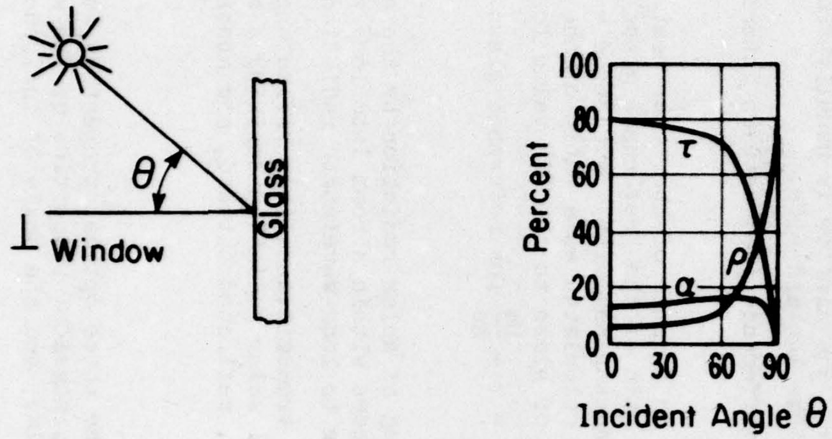

Figure 2-2 Variation in Optical Properties for Typical 1/4 inch Plate Glass

Clear glass is an optically transparent material while the tinted glass contains additives that reduce the visual transmittance and shading coefficient and modify the color appearance. The reflective glass consists of a transparent metallic oxide coating which is applied to the surface of the clear or tinted glass. For single sheet glass the reflective coating is normally placed on the outside surface. For double or insulating glass, the reflective coating can be placed on the outside surface of the outdoor glass, or the air space surface of the outdoor glass, or the air space surface of the indoor glass. The outdoor glass and indoor glass can both be clear or the outdoor glass can be tinted while the indoor glass is clear.

Glass has a specific gravity of 2.40 to 2.60 and weighs approximately 156 to 158 lb/ft^3. This is heavy for most building material. For example, concrete has a weight of 144 lb/ft^3 while common brick weighs 120 lb/ft^3. A more meaningful way to express the weight of glass is in terms of its weight per square foot of surface area. Therefore a 1/4 inch thick glass will weigh between 3.25 and 3.29 lb/ft^2.

Strength of the glass is a key consideration in the selection of glass. The strength attributes are expressed in terms of the thickness of glass required. The thickness is a function of the external pressure loading (wind, sonic, etc.), the surface area of the glass, strength properties of the glass, surface characteristics of the glass, and the support conditions.

Environmental Impact on the Window. 1. Thermal Characteristics. The thermal characteristics of the glass with or without shading devices is an important property that must be considered. The heat gain and/or heat loss properties of glass will have an influence on the initial and operating cost of the mechanical conditioning system which in turn will influence the level of human comfort and performance. Increases in heat gain (or loss) will occur from an increase in the shading coefficient, U-value, and air-to-air temperature difference.

The U-value represents the reciprocal of the sum of the thermal resistance values of each material including air spaces and surface films. The following table gives an indication of the change in U-value for various conditions.

U-Values[38]

	Summer[a,c]	Winter[b,c]
Single Glass	1.06	1.16
Double Glass	.61	.65
Triple Glass	.45	.47

a - Outside Air Film - Summer @ 7-1/2 mph; $f_o = C = 4.0$

b - Outside Air Film - Winter @ 15 mph; $f_o = C = 6.0$

c - Inside Air Film - Still Air, $f_i = C = 1.46$

One manufacturer listed the U-value for a single sheet of glass as 1.0 for winter conditions (15 mph) which results in a $R_{glass} = 0.15$.

If U = 1.0, then

$$R_{Tot} = \frac{1}{1.0} = 1.0$$

Winter, $f_o = C = 6.0$, then

$$R_{f_o} = \frac{1}{6.0} = .17$$

Interior, $f_i = C = 1.46$

$$R_{f_i} = \frac{1}{1.46} = \underline{.68}$$

$$R_{surface\ films} = .85$$

$$R_{glass} = R_{Tot} - R_{surface\ films}$$

$$R_{glass} = 1.0 - .85 = .15$$

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[38]McGuinness, W. and Stein, B., Mechanical and Electrical Systems for Buildings, 5th Edition, John Wiley and Sons, Inc., New York, 1971.

In the above table of values[38], the resistance of glass is:

$$R_{glass} = 0.01 \quad (U = 1.16)$$

An example in the ASHRAE Handbook of Fundamentals[39], Chapter 22, page 398 gives the resistance of glass as:

$$R_{glass} = 0.035 \quad (U = 1.13)$$

This gives a variation in U-value from 1.0 to 1.16 with an apparent variation in R from 0.01 to 0.15 which appears to be an inconsistency in the literature. The lower the U-value the lower the heat gain or heat loss.

2. Sound Characteristics. The sound transmission loss for various types of glass varies from approximately 24 to 40 dB for frequency range of 125 to 4,000 hertz. The transmission of noise from the exterior environment into the interior environment is dependent on the air-tightness of the building. Street or traffic noise transmitted through and around the glass can be annoying and distracting. In addition to the exterior noise transmission, the window and frame combination may create noise or rattle due to vibration of improperly fitted materials.

3. Maintenance Characteristics. Maintenance of the glass is important to maintain the level of light transmission and desirable visibility. The length of time between cleaning periods is a function of the internal and external environmental conditions. Maintenance of the interior surface of the glass will usually be more convenient which should result in a more repetitive cleaning cycle. For multi-story, fixed window systems, exterior cleaning is more difficult and costly resulting in longer cleaning cycles. With longer cleaning cycles for exterior glass surfaces, loss of light transmission can vary substantially depending on the characteristics of the exterior environment. The percent of transmission loss for one study (*IES Lighting Handbook*[1], Fig. 7-31) indicated a variation in maintenance factor of 73% for a "typical clean location" to 55% for a "typical dirty location" after 6 months.

Example: $\tau_{glass} = 85\%$

τ after 6 months,

$\tau_{glass} = 0.85 \times 0.73 = 0.62 = 62\%$ "Clean Location"

$\tau_{glass} = 0.85 \times 0.55 = 0.47 = 46\%$ "Dirty Location"

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[39] ASHRAE Handbook of Fundamentals, published by the American Society of Heating, Refrigerating and Air Conditioning Engineers, Inc., New York, 1972.

It is obvious that this loss in transmission can have quite an effect on the quantity of illumination reaching the interior space. Dirt of film deposits on the exterior of the glass surface will also affect the quality of the light and the mode of heat transmission. The quality of the light will probably be more diffuse in nature resulting in more nondirectional scatter of the light entering the space. The heat transmission will be affected due to the change in the surface air film characteristics which will affect the f_o value.

Abrasive cleaners should be avoided when cleaning glass to prevent scratches. Fingerprints, grease, dirt, scum, and glazing materials can be removed with a wash, rinse, and dry technique recommended by the manufacturer. A mild soap, detergent, or slightly acidic cleaning solution can be used to wash most glass surfaces. For some types of glass and surface grime, mild commercial solvent can be used. Glass with reflective coatings can be damaged or scratched if not cleaned properly. Alkaline or fluorine material which is associated with concrete, masonry, or decorative crushed rock can stain or etch the glass. Oxide deposits from weathering steel or rust can also stain or etch glass.

Maintenance of toplight or skylight systems can be more critical in terms of accessibility and dirt accumulation. The horizontal orientation of a toplight system will accumulate dirt more rapidly than a vertical surface. Cleaning of the toplight from the outside may be easier than cleaning the outside of vertical windows; however, accessibility to interior toplight surfaces may be more difficult. Interior surface cleaning may require ladders or scaffolding to be brought into the space which may discourage cleaning. Deposits of dirt and surface film materials such as smoke present in the environment will adversely affect the efficiency of transmission and the distribution characteristics. Static charges which are common with plastic surfaces found in toplight systems may compound the maintenance problem.

4. Control Elements. Control elements are introduced to prevent the direct transmission of the sun, to reduce glare, and to reduce heat gain and heat loss. The control elements can be internal or external. They can be an integral part of the window or a separate element from the window (Fig. 2-3).

Direct transmission of radiant energy, from the sun should be prevented to minimize luminance ratios within the interior environment as well as to prevent color fading. Shielding elements both interior and exterior can be used. Exterior shielding elements would include overhangs, louvers, building elements or projections, and landscaping. Interior shielding usually consists of shades, blinds (vertical and horizontal),and draperies. Interior shielding has the disadvantage of allowing the penetration of the radiant energy into the space which will be converted to heat and result in a heat gain due to the greenhouse effect. Interior shielding is used more often than exterior shielding because of its accessibility and the ease of maintenance. To be effective as a shielding device, the material must be opaque or of very low transmittance.

Glare control can be achieved by reducing the apparent luminance of the window surface or moving the glare source out of the direct field of view. Reductions in luminance or luminous intensity entering the interior

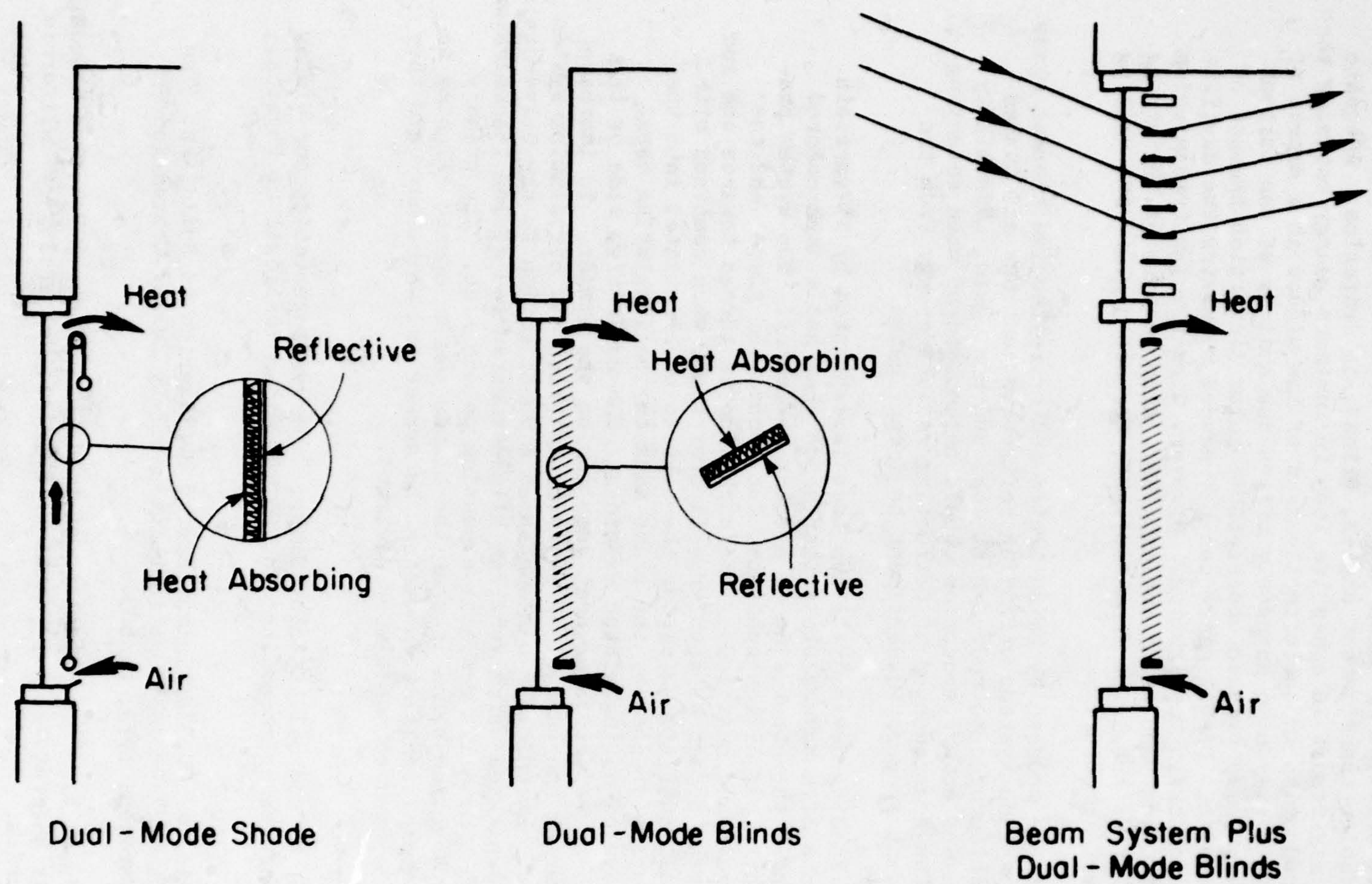

Figure 2-3 Daylight and Heat Control Devices

environment can be achieved by using tinted or low transmission glass or by using low transmission transluscent shades, blinds, or draperies. Adequate control of glare may result in excessive loss in luminous energy entering the space causing a reduction in the effectiveness of the window as a source of light. Glare control may also adversely affect the ability of one to look out of the window and may produce unacceptable color distortion because of selective transmission. Direct glare can be reduced by moving the daylight source overhead such as in toplighting. However, direct solar transmission must also be controlled when using toplighting. Also because of the strong directional quality of the light from toplight, reflected glare and veiling reflections may be a problem.

Heat gain can be reduced by using tinted and/or reflective thermal glass. Double and triple glass systems utilizing reflective coatings and tinted glass have been introduced to reduce heat loss and heat gain. Visibility through the glass and color perception should be considered when selecting thermal glass. The consequences of reflecting radiant energy from the building to adjacent property owners must be investigated.

A Dual-Mode Shading device[40,41] has been investigated by Silverstein. The system consists of a reversible roller shade that has a dark colored absorbing side while the other side is a solar reflector. The system provides for the control of direct sunlight, the control of glare, and the control of heat gain and heat loss. The dark side is turned towards the sun during winter months to act as a solar collector that, when combined with the proper natural ventilation, allows the heat to be circulated into the space. The air space created by the shade adds to the insulating capabilities of the system during winter evenings. The reflective side of the shade can be used to reject solar heat gain during the summer. To increase its efficiency during the summer, an interior-exterior air circulation system might be provided. Rosenfeld[42] has suggested a modification to the Silverstein system. He has suggested using Venetian blinds constructed of low transmission gray plastic with a metallic reflective coating on one side. The primary advantage of the Venetian blind is that the blinds can be opened slightly to allow for more natural ventilation during the summer and on cloudy days they can be partially opened to admit more daylight.

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[40]Berman, S. M. and Silverstein, S. D., "Energy Conservation and Window Systems," AIP Conference Proceedings No. 25, American Institute of Physics, New York, 1975.

[41]Silverstein, S. D., "Efficient Energy Utilization in Buildings: The Architectural Window," Proceedings 10th Intersociety Energy Conversion Engineering Conference, 1973, p. 685.

[42]Rosenfeld, A. H., "Some Comments on Dual Solar-Control Venetian Blinds," Lawrence Berkeley Laboratory, Department of Physics, University of California, Berkeley, California.

A "Beam-Daylighting" system[43] has been investigated to increase the effective utilization of daylighting by increasing daylighting penetration in the space. The system utilizes a Venetian blind with a metallic reflective coating on one side. The silvered "beam" blind is mounted above eye level and utilizes direct solar radiation incident on the top 1 to 2 feet of the window. This "beam" blind is separate from the lower window shading system to allow for independent action. The purpose is to reflect the solar radiation from the "beam" blind to the diffuse white ceiling plane. This indirect lighting system proves greater daylight penetration with more uniform diffusion. The sun orientation, blind tilt, and reflective properties of the ceiling are critical to the efficient utilization of the daylight. Since this system allows for the penetration of direct solar radiation (redirected to the ceiling) into the space, it will result in direct solar heat gain to the interior environment. If the system is not performing at its optimum, sufficient daylighting may not be present to allow for a sufficient quantity of artificial lights to be switched off to offset the heat gain produced by the direct solar radiation.

2.2 DESIGN OF DAYLIGHTING

An analysis of the important aspects of exterior environment (2.1.1), interior environment (2.1.2), and the fenestration (2.1.3) is essential to the beginning of the design process. Each opening placed in the exterior wall of a building should be evaluated in terms of its total impact on the interior environment and the human occupants. The decision to place fenestration in the building should not be based on arbitrary, superficial reasoning. The following is a list of the advantages and disadvantages of placing fenestration in the exterior walls.

Advantages

- Interior/exterior visual communication
- Design Enhancement - rhythm, relief, drama, pattern, etc.
- Ventilation*
- "Opens" the space - feeling of enlargement
- Heat gain in Winter
- Potentially good ESI with proper task placement - See 1.4.1
- Indoor Plant Growth
- Fire Escape
- Security - easier to observe interior with entering the space
- Awareness of exterior environmental conditions
- Visual and psychological relief - varying source of light, changing color, changing mood

*"Ventilation" will increase "Sound Transmission" and the amount of "Air Pollution" to enter the space.

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[43]Rosenfeld, A. H. and Selkowitz, S. E., "Beam and Diffuse Daylighting, and Peak Power," Proceedings: The Basis for Effective Management of Lighting Energy Symposium, Federal Energy Administration, Washington, D. C., October 29 & 30, 1975.

Disadvantages

- •Unpleasant view
- •Glare Source
- •Potential Color Fading & Ultraviolet Damage
- •Heat Loss in Winter
- •Heat Gain in Summer
- •Bodily Discomfort - radiation loss due to surface temperatures
- •Increase maintenance Cleaning & Breakage
- •Higher Cost than conventional wall materials
- •Condensation
- •Undependable, constantly varying light source
- •Shadowing from strong direction source
- •Sound Transmission*
- •Security - easily penetrated
- •Air Pollution - if operable for ventilation*
- •Limits circulation

*"Ventilation" will increase "Sound Transmission" and the amount of "Air Pollution" to enter the space.

The list may not be complete. Each designer may not agree with all factors and should compile his own list. However, this type of listing procedure accompanied by a study of the Analysis Section (2.1) should give the designer sufficient information to make a decision for or against placing fenestration in a room. This decision may vary from room to room depending on the function of the room, its orientation, and its occupants. This statement implies a potentially drastic change in the outward appearance of buildings to more appropriately express the inward function while weighting the impact on energy conservation.

Once the decision has been made to provide fenestration in a space, the size, proportion, and placement of the opening must be decided by the designer. The size should be based on the thermal impact of the opening and the daylighting potential. The proportions and placement should be based on the quality and quantity of daylight entering the space. The following factors should be considered in window design:

1. Avoid the direct penetration of sunlight.
2. For low buildings, one or two stories, use light reflecting ground cover to improve light penetration into the space.
3. Provide openings in more than one wall if possible to improve penetration, uniformity, and reduce harsh shadows.
4. Use high clear glazing - the head of the window is most effective in admitting light to the inner portion of a space.
5. Two rules of thumb:
   a. Optimum daylighting penetration and uniformity will be achieved if the window height is at least one-half the room depth.

b. Glass area should be approximately equal to 25% of the floor area to optimize the uniformity of illumination in a space.

6. The reflectance properties of external shielding devices can be critical to daylight penetration.

The following factors should be considered in toplight or skylight design:

1. Avoid the direct penetration of sunlight.

2. For room monitor, clerestory, and sawtooth configurations, the use of light reflecting roof materials will increase the quantity of light entering the space.

3. Rules of thumb:

   a. Maximum spacing between skylights is 1.5 times the ceiling height.

   b. Skylights should occupy approximately 5% of the ceiling area - this percentage is recommended to minimize ceiling clutter when skylights (5%) are combined with ceiling mounted luminaires (10 to 20% coverage) to allow for a 75 to 85% ceiling surface area which is important to the interreflection of energy.

4. Openings through a flat roof plane create flashing problems which are difficult to solve because of extreme temperature variations causing differential expansion and contraction.

5. Heat build-ups due to natural heat convection currents in a room - heat loss.

6. Moisture seals - condensation prevention and drainage.

2.2.1 Daylighting Design from Windows

Assuming suitable sun control, a southern exposure (continental U.S.) is preferred to optimize the daylight contribution into a space. Sufficient daylighting must be provided to replace artificial lighting if energy conservation is to be realized. North exposure may not provide a sufficient quantity of illumination to allow for a significant reduction in artificial lighting. In general, east-west orientations present the most difficult problems in daylight control and create complicated, extreme heating and cooling problems.

Longhand calculational procedures are based on the data and procedures presented in the *IES Lighting Handbook*[1]. Two longhand methods of calculating illumination levels due to daylighting are outlined in this section and an example of each is given in Appendix H. A computerized design technique is in Appendix I. Although the computer program may be more complex, the user is urged to become familiar with the program. Because of the speed of the computer a more complete and accurate profile of the daylight contribution can be obtained.

The longhand design procedure involves two steps: 1) determine the quantity of illumination coming to the window surface and 2) using that

quantity to determine the daylight contribution to the interior part of the space. To determine the quantity of illumination reaching the window, one of the following design conditions must be assumed.

1. Clear Day (surface exposed to the sun) - the design is based on light reaching the window from three sources.
   a. clear sky
   b. direct sun
   c. ground contribution
2. Clear Day (nonexposed surface)
   a. clear sky
   b. ground contribution
3. Overcast Day
   a. overcast sky
   b. ground contribution

Clear skylight illumination values given in the *IES Lighting Handbook*[1] (Figs. 7-11, 7-12, 7-13, and 7-14) are based on an equivalent clear sky luminance. The single illumination value represents an average of the luminance patterns of the sky for a specific time, data, latitude, and compass direction. The clear sky luminance is assumed to be uniformly distributed across the sky. This assumption of a single equivalent clear sky luminance value to describe the illumination contribution to the window surface is questionable. The direct sun contribution to the surface of a window is given in Fig. 7-8 of the *IES Lighting Handbook*[1]. The illumination values in the table are based on average values. The illumination is on a surface normal to a line from the sun to the window surface. To find the actual level of illumination on the vertical surface of the window, the value must be multiplied by the correct trigonometric functions (see Fig. 2-4).

$$E_{window} = E_{sun} \times \cos\theta_1 \times \cos\psi$$

θ_1 - altitude

ψ - angle between the perpendicular to the window and the vertical plane through the sun

$\psi = \theta_2 - \theta_3$

θ_2 - solar azimuth

θ_3 = azimuth angle to a perpendicular to the window

The illumination produced on a window surface from an overcast sky can be found in Fig. 7-15 p. 7-8 of the *IES Lighting Handbook*[1]. Average equivalent

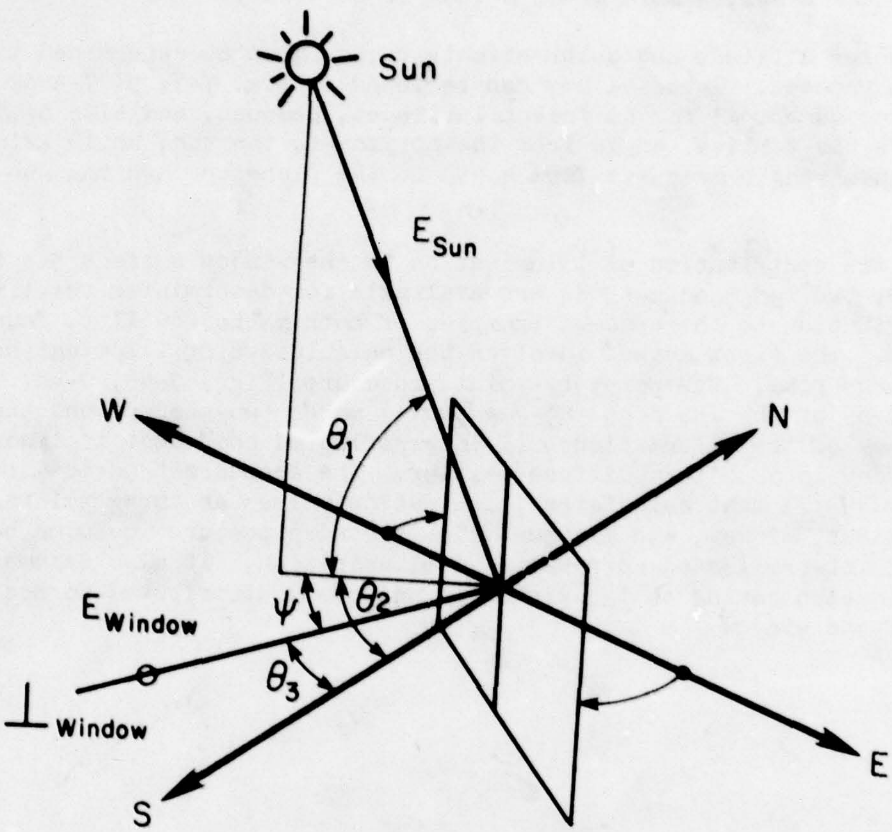

Figure 2-4 Illumination of the Plane of the Window

sky luminance values (Fig. 7-9) for an overcast day are based on the average distribution of luminance across the sky.

Ground light contribution is dependent on the reflectance of the ground cover, the distance between the window and ground, and obstructions. For a ground of infinite extent with uniform luminance, the illumination contribution from the ground can be assumed to be equal to one-half the ground luminance. The ground luminance is calculated by multiplying the horizontal illumination on the ground by the reflectance value of the ground cover material. For limited ground areas, a more exact method is necessary.

The solar altitude and solar azimuth values must be determined to begin the design process. These values can be found in Fig. 7-7, p. 7-4 of the *IES Lighting Handbook*[1] for different latitudes, seasons, and time of day. Altitude is the vertical angle from the horizon to the sun, while azimuth is the horizontal angle measured from south to the plane through the sun (Fig. 2-4).

Once the contribution of illumination to the window surface has been calculated, two longhand methods are available for determining the illumination contribution to the space. Examples of both methods will be found in Appendix H. The first method involves the calculation of illumination at points in the room. The point-by-point procedure (Figs. 9-45, 9-46, 9-47, and 9-48 pg. 9-59 of the *IES Lighting Handbook*[1]) makes two assumptions that affect the accuracy of the calculation: 1) interreflected component is ignored and 2) the window is a uniform diffuse emitter. The second method is a lumen method (pg. 9-77) that calculates illumination values at three points defined as the maximum, midway, and minimum. The second procedure includes both the direct and interreflected components of illumination. It also assumes that the illumination coming to the window is uniformly distributed across the surface of the window.

III. CONTROLS

The previous two sections of this manual have described the necessary information for providing sufficient light for the task of seeing either with artificial or daylight sources. Underlying these techniques has been the requirement to save energy and at the same time maintain visual performance. Energy is the product of the power used by a load and the amount of time that the load is in use (Power = volts x amperes x power factor and Energy = power x time). In other words, to be energy minded, not only the amount of electricity used but also how long it is used must be taken into account.

In the article, "Exploding Some Myths About Building Energy Use"[44], Lawrence G. Speilvogel points out a number of facts collected by various agencies that led him to state "the one factor that, more than any other, determines energy consumption of a building is how it is used." In particular, a plot of the installed lighting watts per square foot versus the total lighting energy consumption of buildings across the country shows no correlation, Fig. 3-1. If there is no correlation between designed watts per square foot and total energy used, what are the factors involved in the total energy consumption? Most experts agree that one factor is the control of the system.

The numerous methods to control the lighting energy consumption fall into two basic categories. The first type of control provides for either an ON or OFF state; the second category provides ON-OFF control, but in addition provides the ability to select a level of energy consumption between on and fully off. This section discusses ON-OFF controls, level controls, and the state-of-the-art of a combination of the two.

3.1 ON-OFF CONTROLS

The basic on-off control is the switch. Switches are available in a number of configurations, each suited to a particular function.

3.1.1 Circuit Breaker Switching

The National Electric Code requires all branch circuits to have circuit protection. Most branch circuit protection today is accomplished with Circuit Breakers. To save initial costs, many designs use that Circuit Breaker to switch the load. Although the initial cost of a switch leg is saved, Circuit Breakers should not be used in place of switches. The use of Circuit Breakers as switches is energy inefficient. Most often the location of the panel board

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[44]Spielvogel, L. G., "Exploding some myths about building energy use," Architectural Record, February 1976, pp. 125-128.

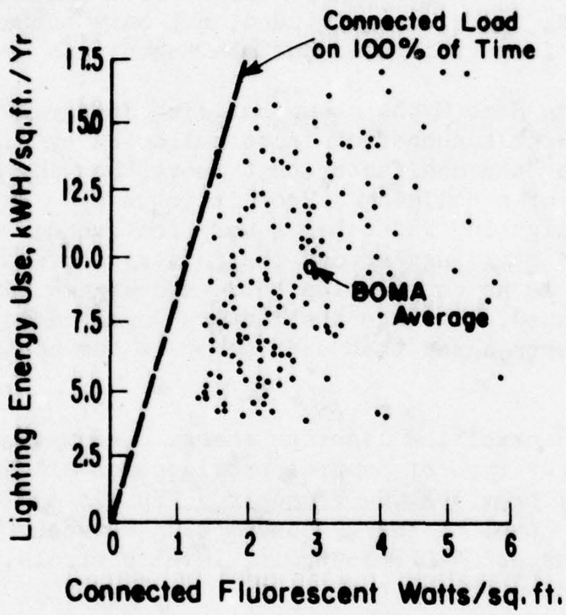

Figure 3-1 Office Building Lighting Energy Consumption Versus Installed Watts

is inaccessible to the occupants of the space being served. In such a case, the occupants have no control over their lights and as a consequence the lights will burn even when not needed. Also a 20-ampere branch circuit loaded to maximum capacity according to code can handle 9 four-lamp fluorescent luminaires at 120 volts or 22 four-lamp fluorescent luminaires at 277 volts. In large areas, all of the units may be needed at one time, but in offices or small areas this approach results in more than one space being served by a single Circuit Breaker. This will prevent energy reductions because it keeps individual office occupants from turning off the lights as they leave the space. Although this method is often used, it is not recommended and should be avoided if energy savings are to be realized.

3.1.2 AC Snap Switches

The most common on-off device is the AC snap switch. The AC snap switch can be located almost anywhere within the room and can carry the full branch circuit load. For example, each private office should have at least one switch for the lights within that space and larger areas can be broken up into distinct work areas with a switch in each area. For a space with more than one entrance three-way or four-way switches should be used to provide control at each entrance.

When a number of switches are provided to control the lights in a large area, they should be circuited with the function of the space dictating the configuration. As an example, consider a lecture hall in which projection equipment is often used. One pattern of circuiting is shown in Fig. 3-2. With switching circuited in this way there are always lights on in the front of the room. Fig. 3-3 is a more logical switching pattern that allows the lights in the rear of the room to remain on for taking notes while those in the front can be turned off to increase the contrast of the screen image. Open plan or office-scape designs are becoming more popular because of increased space utilization and flexibility. Separate controls can be provided for each indirect luminaire and task light at each luminaire location. This allows for selective control of ambient lighting as well as task lighting as the space utilization changes during a day.

Although the AC snap switch is inexpensive and the most commonly installed control device it has many disadvantages because it carries line voltage (120 or 277 volts). Although its safety record is good the possibility of death or serious injury is greater at these voltages. Also, to place the switch in its optimum functional location can be economically prohibitive because of wiring costs as well as increased voltage drop due to long runs. The length of runs and cost become more of a factor with the use of three- or four-way switches.

As an example of dollar savings as well as energy savings, consider four offices with two four-lamp luminaires per office, each office used 9 hours per day, 5 days per week. In one case, there is one switch controlling all the offices and in the other there is one switch per office. The second alternative makes the assumption that each person is out of his office 3 hours per day and that he will turn off the lights whenever he leaves. This second assumption is optimistic, since most studies indicate that people do not turn

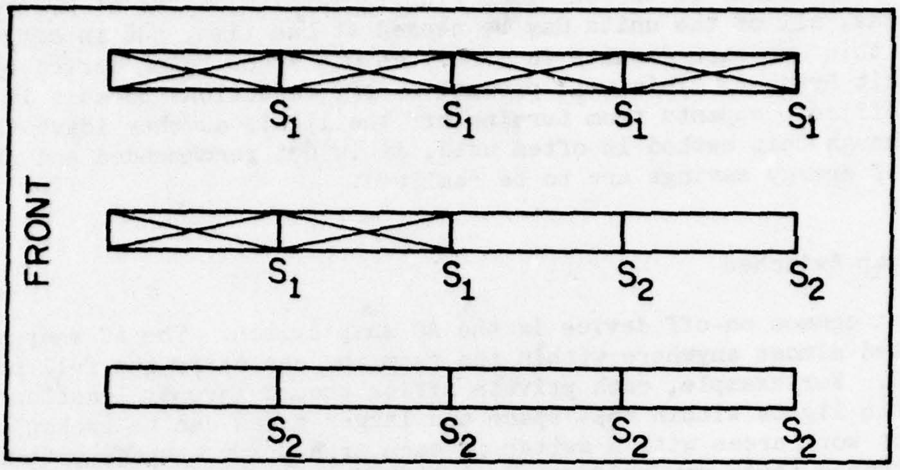

Figure 3-2 Switching Diagram A

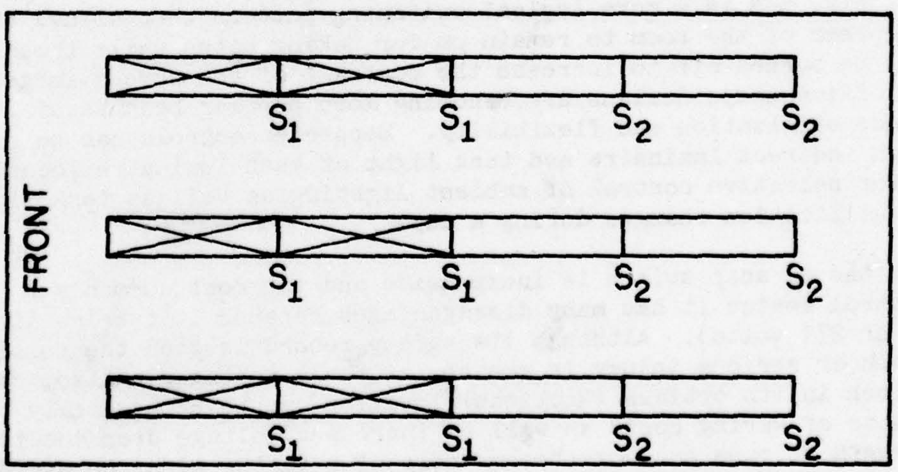

Figure 3-3 Switching Diagram B

off lights when leaving a room.

	Case 1	Case 2
Initial Cost	1 switch and wiring $13.00	4 switches and wiring $52.00
Annual Electricity Costs	8 luminaires x 200 watts/luminaire x 9 hr/day x 260 days/yr 3,744 kwh/yr	8 luminaires x 200 watts/luminaire x 6 hr/day x 260 days/yr 2,496 kwh/yr

It costs $39.00 more for four switches and associated wiring, but saves 1,248 kwh/yr in electrical usage. The cost of electrical power would have to be 3.125¢/kwh to recover the cost of the added switches in 1 year. In many areas of the country, the cost of electricity is far above this rate; therefore, Case 2 would be more economical than Case 1.

3.1.3 Time Switches

Above the assumption was made that a person would turn off the lights in his space whenever he left the room. This is not always true, so it has been suggested that systems be used to take over turning off the lights. One such device is the time switch, most often used with sunlamps installed in bathrooms. One manufacturer provides models with timed cycles of 0-5 min, 0-15 min, 0-30 min, 0-60 min, 0-6 hr, and 0-12 hr. They also have 0-3 min, 0-60 min, and 0-12 hr times that feature a "hold" position for leaving the circuit closed continuously. The price is reasonable at about $10 each.

With a time switch, the occupant of a space must actively turn on the lights but has to take no action to turn them off. Since the behavior of individuals related to the control of lighting is not really known, the economics of the time switch should be compared to both the single switch control of four offices and individual control in each office. In the previous analysis, it was assumed that 3 hours of the day would be spent out of the office. It is probable that part of that time is for short durations in which a time switch would remain on. Therefore, the time out of the office will be reduced to 2 hours with the use of time switches.

Case 1	Initial Cost	- 1 switch and wiring	$ 13.00
	Annual Electricity Costs	- 1600 watts x 9 hr/day x 260 days/yr x 4¢/kwh (assumed)	= $149.76
Case 2	Initial Cost	- 4 switches and wiring	$ 52.00
	Annual Electricity Costs	- 1600 watts x 9 hr/day x 260 days/yr x 4¢/kwh	= $149.76

Case 3	Initial Cost	- 4 time switches and wiring	\$ 92.00
	Annual Electricity Costs	- 1600 watts	
		x 7 hr/day	
		x 260 days/yr	
		x 4¢/kwh	= \$116.48

Using a 25-year economic life and 10% cost of money, the SIR (Saving Investment Ratio)[45]

$$SIR = \frac{\text{present value of future savings}}{\text{present value of incremental investment cost}}$$

$$= \frac{\text{present value factor x yearly savings}}{\text{present value of incremental investment cost}}$$

is calculated. The SIR of Case 3 to Case 1 is

$$SIR_{31} = \frac{9.524 \times \$33.28}{\$79} = 4.0$$

and the SIR of Case 3 to Case 2 is

$$SIR_{32} = \frac{9.524 \times \$33.28}{40} = 7.9$$

Any SIR greater than one economically justifies the added investment. In this situation, it is economical as well as energy efficient to install time switches when the cost of electricity is 4¢/kwh. There are other spaces, such as warehouses, bathrooms, janitor closets, or storerooms where personnel enter the space for short periods of time and neglect to turn off the lights. Time switches would prove even more advantageous in these applications. Where conventional (snap) switches are installed and used, the additional cost of installing time switches is obviously not warranted.

The major disadvantage of time switches is the audible ticking of the timing mechanism. In small areas, such as offices, this could be annoying. It would be counterproductive to improve the luminous environment and adversely affect the acoustical environment.

3.1.4 Low Voltage Switching

Low Voltage Remote Switching is not new on the market, but is gaining in importance. All low voltage systems consist of a magnetic relay, a transformer

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[45] Navy Publication NAVFACINST 11010.53.

(putting out 24 volts or less), and switches which are interconnected with low voltage wiring. The relay switches the line voltage and current with a low voltage command from a low voltage switch in the space. This provides the ability to control loads from great distances, control a number of different loads from one location, and control one load from multiple locations. Two pamphlets printed by manufacturers of Low Voltage equipment - Low Voltage Remote Control Switching from General Electric, Wiring Device Business Dept., Providence, RI 02940 and Low Voltage Lighting Control from Robertshaw Controls, 1800 Glenside Drive, Richmond, VA 23226 - are recommended for specific circuit suggestions.

A low voltage system has many advantages. Since all switch legs carry 24 volts or less there is greater safety, lower copper costs (smaller gauge wires), and lower installation costs since conduit or a raceway system is not required in most states. Switches for a space can be placed in many locations such as the supervisor's office or guard station. Flexibility can be achieved easily with low voltage control. Each luminaire or any group of luminaires up to branch circuit capacity can be grouped on a relay. The switching pattern then can be put together by connecting the low voltage wiring and switches as needed.

One possible configuration would be to switch off all the office lights in a building just after work hours. Then if anyone desires to stay and work overtime, they may turn on the lights again using a low voltage switch located in the area.

With the advent of computers to control building functions, the use of low voltage control of lighting will become more important. One manufacturer is developing computer interface modules.

Low voltage remote control switching becomes more attractive economically as the size and complexity of the control system increases. The initial cost of a low voltage system may be higher than conventional methods. The initial cost is dependent on the scope and complexity of the design. The transformer, relay, wire, and switch costs may be offset by reduction in wire and installation costs. The selection of a low voltage system based on a lower initial cost does not take into account the savings in electricity because of added control.

3.1.5 Time Clocks and Photocells

The controls discussed in the previous sections require some human action to initiate a change of state. Time clocks and photocells, on the other hand, do not require any human action. Time clocks and photocells are discussed together because they are conventionally used to control outdoor lighting such as security, parking lot, roadway, and area. Other than initial cost there is no reason for not using these systems inside. There are a diverse number of both time clocks and photocells that provide different degrees of control.

The most elementary time clock has a single ON time and a single OFF time each day of the week. It has no provision to adjust for the seasonal changes in sunrise and sunset and thus must be continually adjusted when used in

outdoor applications. For indoor applications, such as offices, there is usually no need to adjust ON-OFF times, but on weekends it is desirable not to turn on the lights.

To overcome the disadvantage of continuous operation over the weekend, a time clock that is able to skip a day is available. One model provides for skipping days, but still has a single ON and a single OFF time for the days not skipped.

If a different ON or OFF time is needed for certain days and/or days need to be skipped, a 7-day time clock should be used. Again, though, seasonal changes in dawn and dusk must be manually compensated for when used in outdoor applications.

Designed to take into account seasonal changes in the day-night cycle, astronomic clocks that have a special driving gear are available. No adjustments are needed but they must be ordered knowing their final use location. Besides turning off at dawn, the clock can be set to turn off anywhere from 8:30 PM to 2:30 AM. An example of this feature would be a parking lot that is never used after a certain hour at night.

Rather than using time to determine when the lights should be on or off, photocells or photocontrols can be used to sense when the light level decreases (sunset) or increases (sunrise). Some photocontrols are constructed so that the level at which they are activated can be varied. This is done simply by a movable plate across the cell face.

Photocells can be used alone or in conjuction with other devices. To provide lighting at sunset that is not needed all night, a photocell can be used to turn on the lights, while a time control would turn them off at a preset time. When interfaced with low voltage remote switching, photocells provide another means of controlling the lighting system and its energy consumption.

Photocells are an excellent choice of control because they are simple, maintenance free, independent of a source of operating power, and "self-adjusting" to seasonal changes.

3.1.6 Ultrasonic Detectors

Whether control of the lights should be fully in the hands of the people using the space is debatable. If everyone were energy-minded and always remembered, there would be no need for devices that work independently of human interaction. But this generally is not the case. A device that operates independently of human action, although not used in lighting presently, is the ultrasonic detector.

Designed and used for security (alarm) systems, the device detects the presence (by movement) of persons within the room with ultrasonic waves. Obviously the development of such a device to switch lighting would completely remove the question of human behavior and result in optimum energy utilization. A person entering a room would cause the lights to come on and remain

on until the person leaves. This is control of the lighting by the mere presence of an occupant. A switch that would override the ultrasonic and provide for OFF control would be needed only in rooms where projection equipment might be used. The units that are on the market now are used for intruder detection, and are expensive. With the increased cost of energy and decreasing availability, an ultrasonic switch could prove economically justifiable.

3.2 LEVEL CONTROLS

Section 3.1 discussed a variety of means and devices for turning lights on and off. Many circumstances exist where a level of artificial illumination somehwere between fully on and off is desired. This section deals with devices that control the level of illumination.

3.2.1 Dimmers

The best means of controlling the level of illumination is the dimmer. The original dimmers were resistance types that diverted some of the current through a variable resistor. Although the resistance dimmers have their advantages and disadvantages, the only characteristic of importance here is that they do not save energy. The total power used is the same whatever the light level, because the dimmer itself draws power. Most existing dimmers of this type are used exclusively in theatrical applications.

In the last 10 years, the solid state dimmer has taken over 99% of the dimmer market. The principle of operation is simple. The current in an AC power system is a periodic function as depicted in Fig. 3-4. The power delivered to the load is a function of the shaded area under the curve. The electronic dimmer, by means of an "electronic switch", turns off the current to the load for a portion of the cycle as in Fig. 3-5. Note that the shaded area under the curve is less and thus less power is being delivered to the load. The "electronic switch" has a continuously variable operating time from fully on to fully off. Since the current cannot come on instantaneously as the vertical line would suggest in Fig. 3-5, there is a slight slope or rise time. The current will also overshoot the AC current curve a bit, after which it will oscillate a short time. The overshoot and oscillation causes RF (Radio Frequency) noise and lamp filament ringing. Most manufacturers provide for RF suppression and have chokes available which reduce filament ring. Refer to manufacturer's catalog for specifications.

Solid state dimmers are now made for incandescent, fluorescent, and HID lighting. Incandescent dimmers, which only require the "electronic switch" and RF suppression, are available in a wide range of power capacities. Wall box units are available from 600 to 2000 watts. Other systems which use dimmer packages remotely located from the intensity control switch are available in sizes from 100 to 300,000 watts. The remote dimmer pack systems are available with multiple remote control stations or with a control system that allows push-button selection of a number of preset levels, full range control, and override on-off. Incandescent dimming is the only type that can be dimmed from 100% of full light output to 0%.

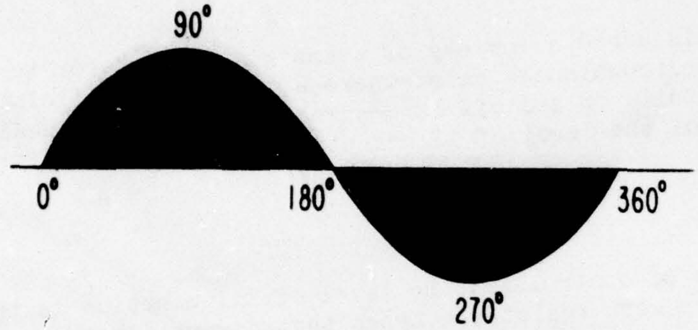

Figure 3-4 AC Current Waveform

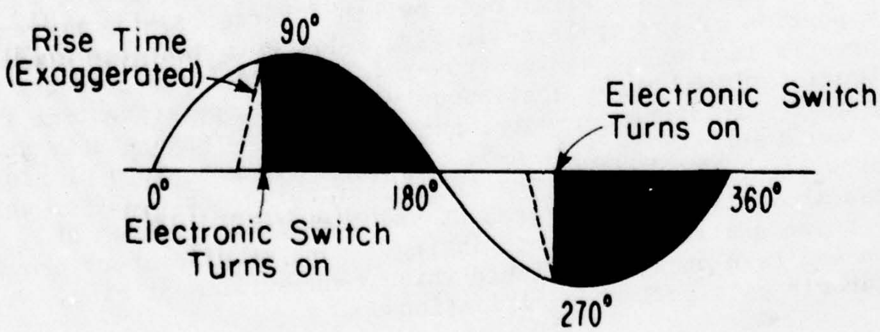

Figure 3-5 AC Current Waveform From a Dimmer

Fluorescent dimmers were first introduced on the market about 1962. Not interchangeable with incandescent dimmers, they require different circuitry, a special dimming ballast, and special lamp holders. Unlike incandescent lamps, the fluorescent lamps being dimmed never go off completely. The minimum light output of any system on the market is 1/500 of the maximum. This is sufficiently low that they appear to be off. Up to 30 40-watt lamps may be dimmed by a single wall box mounted dimmer, while up to 80 lamps may be controlled by a single dimming module. The dimming module system requires intensity controls to be mounted remotely from the dimming module. Because of this, dimming modules may be ganged or combined with incandescent modules. The remote control, high capacity systems may also be outfitted with the preset type controls. A new system introduced by one manufacturer uses an intensity control, dimming module, and electronic package that replaces the ballast. Fig. 3-6 shows the increase in efficacy of this new system over the conventional dimming arrangement.

With the increased use of HID lamps, it is desirable to have dimming for them. Mercury vapor dimming systems are currently available from three manufacturers. One requires no ballast and as a consequence is much quieter than ordinary systems. Because the arc must be maintained, minimum light output of any system is 2% of maximum. The mercury dimming system requires a dimmer module with remote intensity control and is available with a preset control package. Systems for dimming metal halide and high pressure sodium systems are available.

The dimmer modules used in the "high power" fluorescent and incandescent, and HID systems are ideal for interfacing with time clocks, photocells or computers. One such system has been developed by one manufacturer for the control of a mercury vapor system. It consists of a photocell, dimmers, and a control station to monitor the illumination level and the dimmers. The selected level of illumination is maintained by adjustments of the dimmers by the controller as changes in lumen output, daylight contribution, and dirt accumulation occur. Development of a similar system for fluorescent or incandescent lighting would be valuable.

Dimming systems for fluorescent and HID lamps are complex and expensive. The problem lies in the inductive ballasts. Electronic, high frequency ballasts which would make dimming easier and less costly have been developed but not marketed for fluorescent lamps. A simple variable resistor or capacitor added to the circuit is said to allow for simple, easy dimming.

Dimmable lighting systems are expensive, and may not be applicable for every installation, but will result in energy savings if used properly. Dimmers should be used only where it is anticipated that level control will be needed and used.

3.2.2 Multilevel Ballasts

A second method of level control introduced in the past few years has been the multilevel ballast. The purchase of a small number of different items results in an increase in the initial cost of a building. With multilevel ballasts, only one type of luminaire and ballast need be specified for

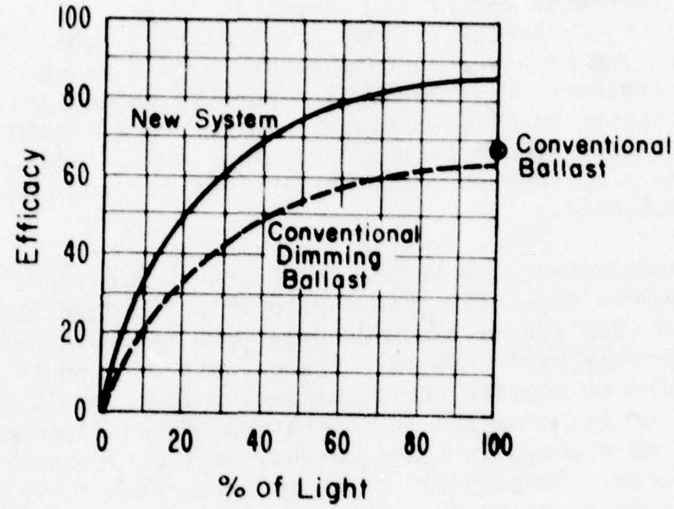

Figure 3-6 Efficacy vs Light Output of Conventional and New Fluorescent Dimming Systems

the job. Adjustments in levels of illumination can be made by a simple wiring change. When retrofitting of existing installations is necessary, multilevel ballasts can save money and energy in areas that were overlit without greatly sacrificing uniformity[46].

Multilevel ballasts are available in two- and three-level models. The two-level ballast provides for 100% light output at 98.7 watts input using two F40T12 RS lamps and 55% light output at 55.7 watts. The three-level has 100%, 55%, and 37.8% light output at 98.7, 55.7, and 37 watts, respectively. One disadvantage of the multilevel ballast is that it requires an electrician to make the level change by rewiring the ballast. Local code authorities may not allow a switch to be placed in the level leads of a multilevel ballast. A two- or three-position switch mounted in the luminaire would make illumination level control easier and eliminate the need for an electrician to make the modification.

3.3 STATE-OF-THE-ART

A paper presented at the 1976 IES Annual Convention[47] describes a computer controlled lighting control system. It combines remote on-off control with two-level illumination selection. The system consists of a controller and receiver/switch. The controller is a microcomputer and oscillator. The receiver/switch is a decoder and two relay switches. The microcomputer is programmed for different lighting patterns and the addresses of the luminaire. The address and condition codes generated are modulated by the oscillator and superimposed on the building electrical system line frequency. The "message" travels through the building electric distribution system. At the receiver/switch, a decoder takes the "message" off the line and if the address code corresponds to the one given that switch, the condition codes are executed, turning the luminaire fully on, halfway on, or off. A clock in the computer times the events allowing for different lighting patterns to be executed at different times of the day.

The advantages of a system of this type are manyfold. Because the commands are sent from the controller to the receiver/switch through the power lines, no rewiring is needed when retrofitting, no switch legs are needed, and no control wires in addition to regular wiring would be needed. If the cost of the receiver/switch is low, each luminaire in a building could be equipped with one. Since each would have its own address, any lighting configuration could be programmed. As the system exists now only preprogrammed configurations can be executed. With the microcomputer, various inputs can be used, such as time clocks, photocells, and/or remote input devices.

This use of the microcomputer wastes the microprocessor's capability because it functions only when a change of state is called for. Future developments could include feedback from various other building functions.

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[46] New Advance Multi-level Ballasts, product specification sheet, Advance Transformer Co., 1975.

[47] McGowan, T. K. and Feiker, G. E., "A New Approach to Lighting System Control," Journal of the Illuminating Engineering Society, October 1976.

Decisions regarding the building performance could be made and appropriate adjustments executed. One such function could be the monitoring of the peak electrical demand. If demand were exceeding a predetermined level, all building functions would be checked and those not necessary would be shed. The continuing development of microprocessor controlled lighting will bring about the desired flexibility while cutting costs and saving energy.

IV. COMBINED ARTIFICIAL/DAYLIGHTING CONTROL SYSTEMS

This section analyzes the need for combined artificial/daylighting control systems. It briefly describes three systems investigated by the Naval Facilities Engineering Command[48] and makes suggestions for modifications to the control systems.

4.1 NEED

The control of artificial lighting to optimize the utilization of daylight is essential if energy savings are to be realized. If artificial lighting levels are not reduced as daylight contribution increases in a space, the overall energy consumption will increase due to the added burden on the mechanical system. That is, the increase in daylighting must be offset by a decrease in power consumption in the artificial lighting to produce meaningful energy reductions.

The addition of daylighting to artificial lighting will result in excessively high lighting levels near the window (Fig. 4-1(b)). Flexible control systems must be installed to maintain a more uniform lighting level throughout the space (Fig. 4-1(c)). The following diagrams will illustrate the problem.

The simplest, least expensive and most obvious solution would be to provide multiple on-off switching within each room. The cross section in Fig. 4-1(a) shows three rows of luminaires. One switch could be provided to control all of the lamps in row (A). A second switch could be used to turn off half of the lamps in the second row (B), while a third switch would provide on-off night control to row (C) and the other half of the lamps in row (B). When a sufficient daylighting contribution exists in the space, switches (A) and (B) could be turned off to approximate the distribution in Fig. 4-1(d). If the daylighting contribution is inadequate (overcast or night time) or if opaque shielding devices are used to control direct light, all three switches (A, B, C) could be turned on. The switching could be either a low voltage or normal voltage system (Section 3.1).

However, the control system is only as good as its weakest link. In this case, the weakest link in the control system is man. As variations in the daylighting contribution occur during a normal working day, the user may have to adjust the switching. Experience indicates that unless the user of the space is also the one who pays the utility bills, the user will grow tired

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[48]Smith, M. N., "Automatic Light Sensing and Control of Lighting Systems for Energy Conservation," Civil Engineering Laboratory, Naval Constructions Battalion Center, Port Hueneme, California, 1976.

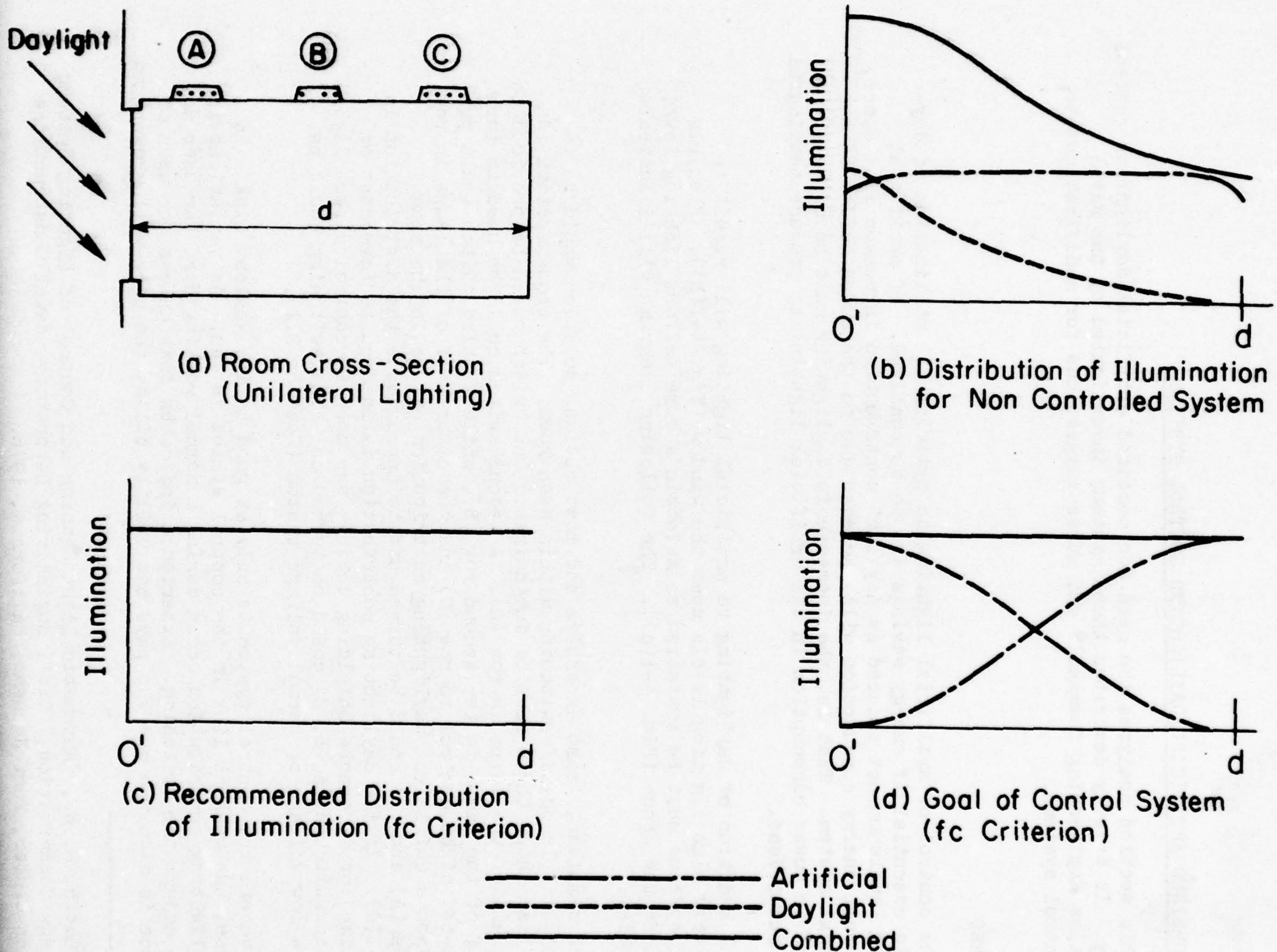

Figure 4-1 Combining Artificial and Daylight Contributions

of making the appropriate adjustments and leave all of the artificial lights on. To conserve energy and optimize the use of daylight, the control of the artificial lighting must be taken out of the hands of the user.

4.2 INVESTIGATION OF THREE CONTROL SYSTEMS

The Naval Facilities Engineering Command conducted an investigation[48] of available automatic lighting control systems. The investigation included an industry survey of commercially available control systems. The report evaluates one commercial and two CEL-developed control systems. The investigation concludes that automatic control systems do conserve electrical energy.

This manual briefly describes the systems investigated and summarizes the findings. For a more complete description, the reader is referred to the complete report[48].

4.2.1 General Electric Light Sensing and Control System

The GE (General Electric) system consists "of a photorelay, a remote-control interface, low-voltage transformer, rectifier, relays, local switch, and override switch[48]." The system uses relays to turn luminaires off when a predetermined level of outside light is achieved. The photocell-sensor is positioned outside to read the lighting level.

The major difficulty encountered in one test installation was the behavior pattern of the user. The personnel working in the test installation normally kept the Venetian blinds closed. On sunny days, the sensor would detect the presence of a sufficient level of light and would switch off the lights in the test installation. The occupants would use the override switch to turn the lights back on rather than open the Venetian blinds.

The investigations reported the results of two additional installations. The payback periods for five different geographical areas ranged from 2.8 to 3.8 years (Table 2)[48] for a hallway installation and from 3.5 to 5 years (Table 3)[48] for a work area installation.

4.2.2 CEL Two-Level Automatic Light Sensing Control

The CEL (Civil Engineering Laboratory) Two-Level Control system consists "of a photocell sensor, threshold level control, initial instant-on, override switch, automatic on-off delay switch, gate driving circuit, and solid state switch[48]." The system uses a time delay circuit to provide power to a solid state switch which turns the lights on when the lighting level in an area drops below a preselected control setting (threshold). When the lighting level exceeds the threshold level, the delay circuit de-energizes the solid state switch to turn off the lights. The on-off delay circuit prevents cycling of the lights when an object, person, or cloud causes a momentary reduction in lighting level to the photocell sensor.

The major difficulty with this system was the distraction created as the lamps cycled on and off. The installation was in a small office in which the level was controlled by cycling groups of luminaires on and off. This exaggerated the cycling effect and created distraction while affecting adaptation. The system was rewired to cycle part of the lamps in all luminaires in the room. This was found to be more satisfactory and less distracting to the occupants. The report shows a payback period for five different geographical areas that ranged from 4.2 to 6.1 years (Table 4)[48] for the single office tested.

4.2.3 CEL Constant Illumination Level Lighting Control System

The CEL Constant Level system consists "of a photocell sensor, input amplifier, level setting comparator, null-indicator, electro-mechanical driver, and dimmer[48]." The system makes use of fluorescent dimmers to maintain a constant level of illumination within the space. Therefore, each fluorescent luminaire must contain a dimming ballast. At this time, the system would be quite expensive for retrofit jobs where dimming ballasts are not present in the luminaires.

The test installation used a single photocell sensor located in the center of the room facing down towards the work surface. This system was superior to the two previous systems because of the more subtle changes in illumination in response to the daylight contributions. The payback period is longer for the CEL-Constant Level system, but the more desirable effect of maintaining a constant level of illumination may be worth the longer payback period. The uniform lighting conditions should result in an increase in productivity and performance because of the subtle changes in illumination level rather than the undesirable cycling and sudden variations experienced with the other systems.

4.3 RECOMMENDATION

The user of a space should be given only one control option (user system), that is, the lighting level control system is either on or off. The changes that occur during the "on" period to compensate for the variations in the daylighting contribution (compensating system) must be compleley automatic. The "compensating system" could involve an on-off mode or a continuously varying mode (dimming). In either mode, the "compensating system" should have a delay circuit that would prevent response to momentary daylight reductions caused by cloud movement. Of the two "compensating systems" the continuously varying mode would be preferred. The cycling effect of the "on-off" mode would be less expensive and better suited for retrofit applications but it could also be quite distracting and annoying. The "user system" which is the on-off control of the "compensating system" should be controlled with a time clock or other device that would automatically turn off the "compensating system" at the end of the day. A short period (maximum 3 hours) manual override would have to be available for those who must work overtime or come in at night. In larger rooms, multiple dimmers and photocell sensors may be required to control separate rows of luminaires to assure a more uniform lighting level throughout the space.

Because of the current state-of-the-art in lighting control systems, the initial cost of such a system would be quite high. However, as technology advances in this field, the competitive market should bring the cost down to a more reasonable level. Also the cost of this type of system must be evaluated in terms of its payback period due to the reduction in operating cost and in terms of its overall comfort to the user.

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APPENDIX A

PHOTOMETRICS

Calculation of Zonal Lumens

Use Luminous Intensity Data on Page 140

Set Up a Table as Below:

Zone	0°	22.5°	45°	67.5°	90°	AMZC	Output Lumens
0 - 10	1667	1589	1591	1592	1592	1600	152
10 - 20	1650	1561	1537	1531	1534	1555	440
20 - 30	1760	1627	1496	1400	1393	1525	706
30 - 40	1843	1693	1521	1266	1201	1500	942
40 - 50	1783	1687	1454	1118	903	1401	1084
50 - 60	818	828	1034	837	587	851	763
60 - 70	451	434	477	526	402	466	463
70 - 80	230	230	208	227	202	220	233
80 - 90	66	61	61	55	41	58	63

Determination of CIE-IES Classification

Σ 0 - 90° = 4846

Σ 90 - 180° = 0

CIE-IES Classification - Direct

Determination of Luminaire Efficiency

$$\% = \frac{\Sigma\ 0 - 180^\circ}{\Sigma \text{ bare lamp lumens}}$$

2 lamps @ 3150 lumens each (page 140)

$$\% = \frac{4846}{6300} = 76.92\%$$

Determination of Luminaire Average Luminance

$$\text{Ave Lum}_\theta = \frac{I_\theta}{\text{Area} \cdot \cos\theta} \times 144\pi$$

Across

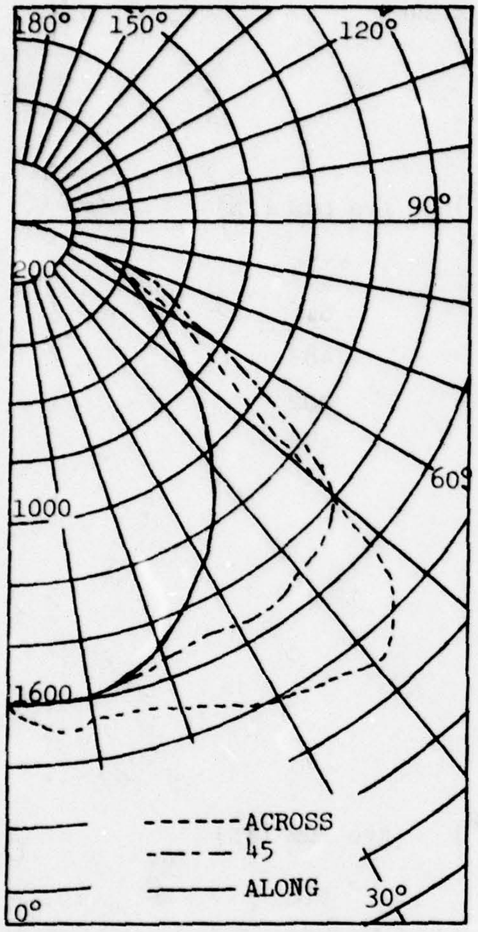
Angle	I_θ(cd)	Proj. Area (in^2)	Ave Lum (fL)
45	1783	706.4	1142
55	818	573.0	646
65	451	422.2	483
75	230	258.6	402
85	66	87.1	343

Along

Angle	I_θ(cd)	Proj. Area (in^2)	Ave Lum (fL)
45	903	706.4	578
55	587	573.0	463
65	402	422.2	431
75	202	258.6	353
85	41	87.1	213

Batwing Lens in 2' x 4' Troffer

Two F40CW Fluorescent Lamps, Rated 3150 Lumens Each



Candlepower Data

Angle	Plane				
	Across	67.5	45	22.5	Along
0	1587	1587	1587	1587	1587
5	1667	1589	1591	1592	1592
15	1650	1561	1537	1531	1534
25	1760	1627	1496	1400	1393
35	1843	1693	1521	1266	1201
45	1783	1687	1454	1118	903
55	818	828	1034	837	587
65	451	434	477	526	402
75	230	230	208	227	202
85	66	61	61	55	41
90	0	0	0	0	0

Total Lumens

Zone	Lumens	Percent
0-40	2237	35.52
0-60	4072	64.64
0-90	4838	76.80

Luminance Summary-FootLamberts

(Lens Area = 999 in^2)

Angle	Across			Along		
	AVG	MAX	M/A	AVG	MAG	M/A
45	1142	2148	1.9	576	730	1.3
55	646	1555	2.4	462	698	1.5
65	484	813	1.7	429	630	1.5
75	403	543	1.3	352	595	1.7
85	345	352	1.0	213	352	1.7

Batwing Lens in Commercially Available 2 x 4 ft Recessed Troffer

Two F40CW Fluorescent Lamps, Rated 3150 Lumens Each

Coefficients of Utilization
(Effective Floor Cavity Reflectance = .20)

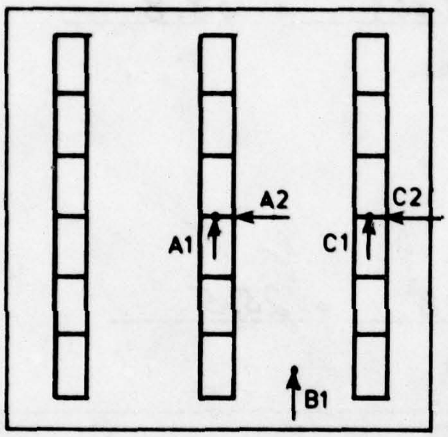
CC	80				70				50			30			10		
WALL	70	50	30	10	70	50	30	10	50	30	10	50	30	10	50	30	10
RCR																	
1	.85	.81	.78	.76	.83	.80	.77	.75	.76	.74	.72	.73	.72	.70	.71	.69	.68
2	.78	.72	.68	.64	.76	.71	.66	.63	.68	.64	.61	.66	.63	.60	.63	.61	.59
3	.71	.64	.59	.54	.70	.63	.58	.54	.61	.56	.53	.59	.55	.52	.57	.54	.51
4	.66	.57	.51	.46	.64	.56	.51	.46	.54	.49	.45	.53	.48	.45	.51	.47	.44
5	.60	.51	.44	.39	.58	.50	.44	.39	.48	.43	.39	.47	.42	.38	.45	.41	.38
6	.55	.54	.39	.34	.54	.45	.38	.34	.43	.38	.34	.42	.37	.33	.41	.36	.33
7	.51	.41	.34	.30	.50	.40	.34	.29	.39	.33	.29	.38	.33	.29	.37	.33	.29
8	.47	.36	.30	.25	.45	.36	.29	.25	.35	.29	.25	.34	.29	.25	.33	.28	.25
9	.43	.32	.26	.22	.42	.32	.26	.22	.31	.25	.21	.30	.25	.21	.29	.25	.21
10	.39	.29	.23	.19	.39	.29	.23	.19	.28	.23	.19	.27	.22	.19	.27	.22	.18

To demonstrate the procedure for calculating ESI footcandles and their relationship to "raw" footcandles, the following example problem is given. Assume that C has been calculated by a predetermination program and the CRF values for selected locations have been calculated.

Given the following preliminary layout investigate the ESI values at three test positions for a 25° viewing angle and three different lens systems.

$CRF = \frac{C}{C_o}$, E_t; L_b - Computed by Computer Program

ρ_o = .808 for the given task



Room Characteristics

28' x 28'

F. to Clng. = 8' - 0"

WP. = 2.5'

ρ_c = 85%

ρ_w = 48%

ρ_f = 18%

Luminaire Types	Position	E_T	L_B	CRF
	A1	112	95.2	.804
	A2	141	109.7	.961
X	B1	121	97.4	1.016
	C1	102	87.2	.778
	C2	137	107.6	.945
	A1	71	56.0	.942
	A2	70	55.2	.995
Y	B1	106	82.7	1.027
	C1	55	44.7	.899
	C2	64	52.3	.988

E_T = Task Illumination - is a measure of the total illumination on the surface of the task (raw footcandles).

L_B = Task Background Luminance - is a measure of the background luminance of the task.

Calculation of ESI

Luminaire Type X Position A1

1. L_B = 95.2
2. Find RCS' based on L_B from Tables.

   RCS' = 73.1
3. CRF = 0.804
4. Compute RCS_e = RCS' x CRF

   RCS_e = 73.1 x 0.804 = 58.8
5. Find L_e based on RCS_e from Tables.

   L_e = 20.6
6. ρ_o = 0.808
7. Compute ESI = L_e/ρ_o

   ESI = 20.6 ÷ 0.808 = 25.5
8. Enter ESI value in the worksheet.

Luminaire Type X Position A2

1. L_B = 109.7
2. Find RCS' based on L_B from Tables.

   RCS' = 74.3
3. CRF = 0.961
4. Compute RCS_e = RCS' x CRF

   RCS_e = 74.3 x 0.961 = 71.4
5. Find L_e based on RCS_e from Tables.

   L_e = 78.9
6. ρ_o = 0.808
7. Compute ESI = L_e/ρ_o

   ESI = 78.9 ÷ 0.808 = 97.6
8. Enter ESI value in the worksheet.

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WORKSHEET

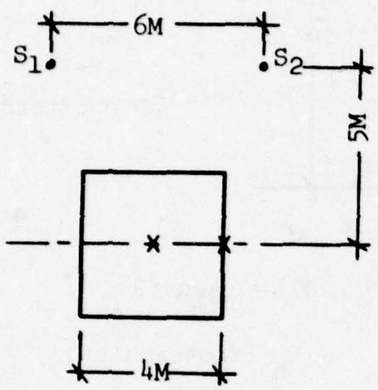
Lens System	Calculation Headings	Position				
		A1	A2	B1	C1	C2
X	ESI fc	25.5	97.6	137.5	19.9	85.3
	E_T Measured fc	112.0	141.0	121.0	102.0	137.0
	LEF = ESI/E_T	0.23	0.69	1.14	0.20	0.62
Y	ESI fc					
	E_T Measured fc	71.0	70.0	106.0	55.0	64.0
	LEF = ESI/E_T					

APPENDIX C

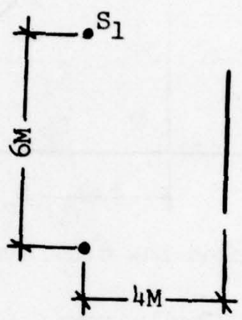
POINT-BY-POINT

Example 1

A painting is illuminated by two lamps (uniform point sources) that each produce 50 candela. The lamps are 6 meters apart, 4 meters from the plane of the painting, and 5 meters above the horizontal center line of the painting. The painting is 4 meters wide and centered between the two lamps. Find the illumination at the center of the painting.

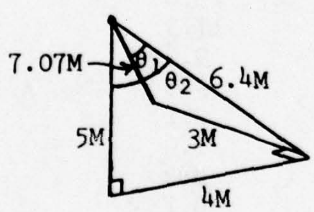


Front View



Top View

Find illumination at the center of painting.



$$E_v = \frac{I}{D^2} \cos\theta_1 \sin\theta_2$$

$$D^2 = 50 \qquad I = 50\text{cd}$$

$$\cos\theta_1 = \frac{6.4}{7.07} = .905 \qquad \sin\theta_2 = \frac{4}{6.4} = .625$$

$$E_v = \frac{50}{50}(.905)(.625)$$

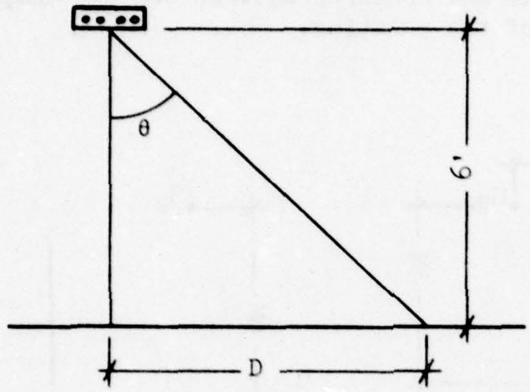
$$= .566 \text{ cd/M}^2 \text{ (lux)}$$

$$E_v \text{ (both sources)} = 2(.566)$$

$$= 1.13 \text{ lux}$$

Example 2

Find the illumination along a line through the center of the luminaire 90^{o} to the lamp axis for the luminaire on page 140 for a mounting height of 6 feet.



$$D = 6 \cdot \tan\theta$$

Use the Cosine Cubed Law of Illumination $E_h = \frac{I}{H^2}\cos^3\theta$

Angle	Candlepower	D	E_h (footcandles)
0	1587	0	44.1
5	1667	0.52	45.8
10	1647	1.06	43.7
15	1650	1.61	41.3
20	1691	2.18	39.0
25	1760	2.80	36.4
30	1796	3.46	32.4
35	1843	4.20	28.1
40	1889	5.03	23.6
45	1783	6.00	17.5
50	1242	7.15	9.2
55	818	8.57	4.3
60	608	10.39	2.1
65	451	12.87	1.0
70	311	16.48	0.3
75	230	22.39	0.1
80	135	34.03	0.02
85	66	68.58	0.001

APPENDIX D

TYPICAL LIGHTING DESIGN PROCEDURE

Design a lighting system for the room shown in Fig. D-1. The Illuminance shall be 100 fc average and the ESI at the task locations shall be 70 ESI for the pencil target viewed at 25°.

Additional Information: Surface Reflectances

ceiling	80%
walls	60%
floor	15%

Foor-to-ceiling height 9.0 ft
working plane height 2.5 ft

Use the luminaire of Appendix A

Use a maintenance factor (LDD x LLD) of .75

The first step in design of a lighting system is to find a probable number of luminaires that will provide an average illumination level. The Lumen Method with Zonal Cavity Coefficients determines the number of luminaires needed to provide an average illumination with a minimum amount of work.

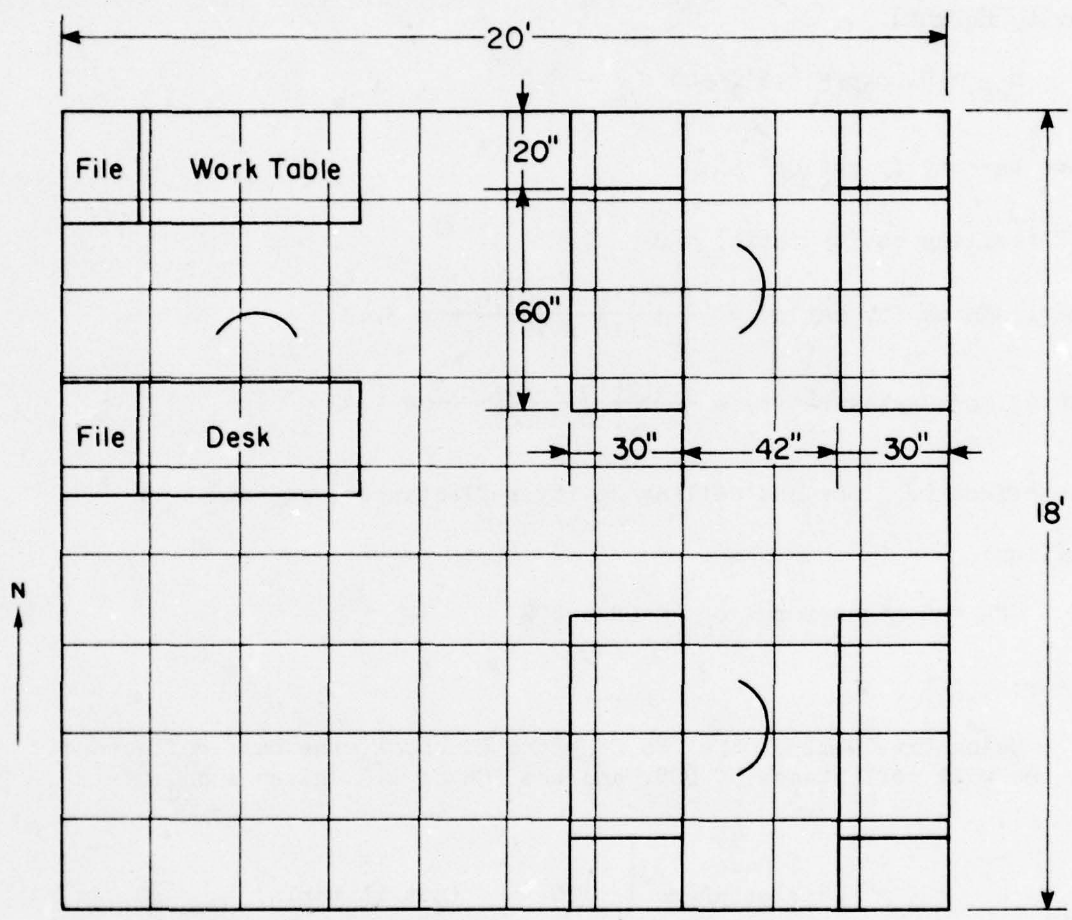


Figure D-1 Room Layout (Scale 1/4"=1')

Lumen Method with Zonal Cavity Coefficients

First list all known quantities as shown in Fig. 1-22

Reflectances

$CWR = 60\%$, $\rho_w = 60\%$, $FWR = 60\%$, $CR = 80\%$, and $FR = 15\%$

ρ_{cc} and ρ_{fc} are to be calculated.

Cavity Heights

$h_{cc} = 0$, $h_{RC} = 6.5'$, and $h_{fc} - 2.5'$

Calculate the cavity ratios

CCR (ceiling cavity ratio) = 0

$$\text{RCR (room cavity ratio)} = \frac{2.5(2(18 + 20))6.5}{(18 \times 20)} = 3.43$$

$$\text{FCR (floor cavity ratio)} = \frac{2.5(2(18 + 20))2.5}{(18 \times 20)} = 1.32$$

Find the effective floor and ceiling cavity reflectances, ρ_{fc} and ρ_{cc}.

Ceiling:

CCR = 0 therefore $\rho_{cc} = CR = 80\%$

Floor:

Using Fig. 9-11 of the *IES Lighting Handbook*, the base reflectance of 15%, the wall reflectance of 60%, and the FCR of 1.32 gives a ρ_{fc} of

	% Base Reflectance	20	15 (not in table)	10
	% Wall Reflectance	60	60	60
	1.2	20	$13 + \frac{20-13}{2} = 16.5$	13
Cavity Ratio	1.32 (not in table)		16.5	
	1.4	20	16.5	13

Next find the CU from the Coefficient of Utilization table of the luminaire

	ρ_{cc}	80	
	ρ_w	70	50
RCR	3	.71	.64
	4	.66	.57

For a ρ_w of 60% the CU for an RCR of 3 is

$$(.71 - .64) \times (\frac{70 - 60}{70 - 50}) + .64 = .675$$

and for a ρ_w of 60% the CU for an RCR of 4 is

$$(.66 - .57) \times (\frac{70 - 60}{70 - 50}) + .57 = .615$$

Therefore

	ρ_{cc}	80
	ρ_w	60
RCR	3	.675
	4	.615

and the CU for an RCR of 3.43 is

$$(\frac{3 - 3.43}{3 - 4}) = \frac{.675 - x}{.675 - .615}$$

$$CU = .675 - (.43)(.675 - .615)$$

$$CU = .649$$

The CU of .649 is for a ρ_{fc} of 20% and previously the ρ_{fc} for this room was found to be 16.5%. Using Fig. 9-13 of the *IES Lighting Handbook* the correction factor for a 10% ρ_{fc} is

	ρ_{cc}	80		
	ρ_w	70		50
	3	.939 →	.945	← .951
			↓	
RCR	3.43		.948	
			↑	
	4	.944 →	.951	← .958

The correction factor for a 20% floor is 1 for all ρ_{cc}, ρ_w, and RCR. To find the correction for 16.5% then

$$\text{Correction Factor} = 1 - [(\frac{20 - 16.5}{20 - 10}) \times 1 - .948]$$

Correction Factor = .982

$CU_{corr} = .649 \times .982 = .637$

Using the lumen formula as follows

$$\text{No. of Luminaires} = \frac{(\text{illumination})(\text{area of work plane})}{(\text{lumens/lamp})(\text{no. of lamps/luminaire})(\text{CU})(\text{MF})}$$

$$\text{No. of Luminaires} = \frac{(100)(18 \times 20)}{(3150)(2)(.637)(.75)}$$

= 11.96 say 12 luminaires

Layout the 12 luminaires uniformly as shown in Fig. D-2.

The Lumen Method is used to determine an approximate number of luminaires. Using the above trial layout an analysis is made with Lumen II. The calculation grid size is 1 ft x 1 ft beginning 0.5 ft from the wall. Fig. D-3 is the illuminance at the points on the grid and Fig. D-4 is the ESI at the points on the grid. Fig. D-5 is the room layout with specific points showing the illuminance and ESI (in the proper direction). Note that the ESI for two points one foot apart on the work surfaces can vary drastically. If we choose the higher value, all work surfaces meet the design parameters except the desk in work Station 1. There are a total of 1104 watts of lighting.

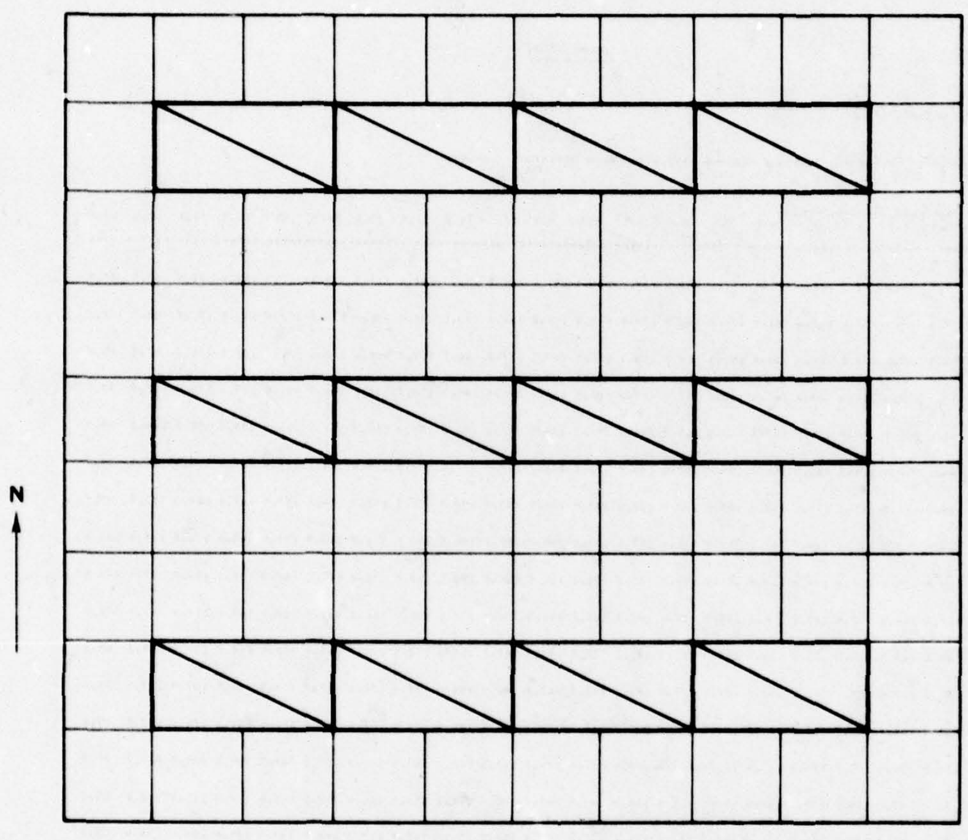


Figure D-2 Uniform Luminaire Layout

ILLUMINATION

WORKING PLANE HEIGHT 2.50

AVERAGE 138.981 MINIMUM 70.556 MAXIMUM 191.971 MEAN DEVIATION 26.402

ABS. Y COOR.	ABSOLUTE X-COORDINATE(S) .5	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5	14.5	15.5	16.5	17.5	18.5	19.5
17.5	72.6	81.0	93.3	102.1	111.4	117.5	123.9	127.4	130.5	131.6	131.4	130.3	127.8	123.9	118.1	112.3	102.6	93.6	82.3	74.2
16.5	77.8	88.3	101.5	112.4	121.9	129.5	135.9	139.9	143.3	144.2	144.2	143.1	140.6	135.7	130.2	122.9	112.6	101.7	90.9	79.0
15.5	83.9	95.0	110.0	122.0	133.4	141.3	148.7	153.1	156.9	158.1	157.9	156.5	153.7	148.7	142.0	134.2	122.3	110.9	97.3	85.9
14.5	88.5	100.4	116.0	128.8	140.4	149.3	157.0	162.0	165.8	166.9	166.9	165.3	162.7	157.2	149.9	141.8	129.7	116.4	102.9	90.0
13.5	94.0	106.2	122.3	135.5	147.7	156.8	165.3	170.3	174.7	176.0	176.0	174.5	171.3	165.3	157.5	149.7	135.8	122.8	108.8	95.6
12.5	96.1	108.4	124.9	138.3	150.3	159.9	168.6	174.0	178.2	179.7	179.6	177.8	174.8	168.8	161.1	152.0	138.7	125.3	111.3	97.8
11.5	98.1	111.0	127.7	141.6	153.9	163.7	172.5	178.0	182.8	184.0	183.8	182.3	178.8	172.9	164.6	155.6	142.0	128.3	113.7	99.9
10.5	99.6	112.9	130.3	144.7	157.7	167.6	176.4	182.4	187.0	188.2	188.0	186.6	183.5	176.8	168.6	159.5	145.0	130.8	115.8	101.4
9.5	100.6	114.4	132.3	147.2	160.5	171.0	179.9	185.8	190.4	191.5	191.8	190.1	186.8	180.1	171.8	162.3	147.4	132.9	117.4	102.5
8.5	100.6	114.4	132.4	147.2	160.6	171.0	180.0	185.7	190.2	191.6	192.0	190.1	186.7	180.1	171.8	162.3	147.4	133.0	117.5	102.6
7.5	99.4	112.5	129.8	143.9	156.5	166.8	175.3	181.0	185.7	187.3	187.2	185.5	182.2	175.7	167.7	158.1	144.2	130.4	115.2	101.1
6.5	97.9	110.6	127.3	141.0	153.5	163.3	171.5	177.1	182.0	183.0	182.8	181.4	177.9	172.0	164.0	154.9	141.5	127.9	113.3	99.6
5.5	95.7	108.0	124.2	137.5	149.5	158.6	167.6	173.2	177.3	178.7	178.5	176.8	173.7	167.8	159.7	151.1	137.9	124.5	110.5	97.1
4.5	93.0	104.9	121.2	134.2	145.8	155.0	163.6	168.6	172.7	174.1	174.0	172.3	169.5	163.3	155.7	147.5	134.4	121.5	107.7	94.5
3.5	88.0	99.6	115.2	127.2	139.3	148.1	155.8	160.5	164.5	165.7	165.6	164.1	161.3	156.0	148.5	140.6	128.2	115.5	102.1	89.3
2.5	83.1	94.3	108.1	120.9	131.9	140.0	147.1	151.6	155.2	156.4	156.2	154.8	152.3	147.2	140.5	132.7	121.0	109.4	96.4	83.9
1.5	76.9	86.6	99.6	110.2	119.7	127.1	133.6	137.5	140.8	141.9	141.7	140.5	138.1	133.5	127.7	120.9	110.1	99.9	88.6	77.8
.5	70.6	80.3	92.1	101.1	109.6	116.1	122.1	125.7	128.6	129.8	129.6	128.5	126.1	122.1	116.5	110.5	101.2	92.0	81.7	73.0

Figure D-3 Illumination Using Uniform Luminaire Layout

EQUIVALENT SPHERE ILLUMINATION

TARGET DESCRIPTION: PENCIL TARGET - CONCENTRIC RINGS # 25 DEGREE VIEWING ANGLE
SPHERE CONTRAST: .1575

WORKING PLANE HEIGHT 2.50

NORTH	EAST	SOUTH	WEST	TOTAL
AVERAGE= 70.492	AVERAGE= 78.191	AVERAGE= 70.840	AVERAGE= 78.336	AVERAGE= 74.515
MINIMUM= 28.898	MINIMUM= 26.202	MINIMUM= 29.166	MINIMUM= 26.161	MINIMUM= 26.161
MAXIMUM= 109.356	MAXIMUM= 133.187	MAXIMUM= 111.407	MAXIMUM= 133.421	MAXIMUM= 133.421
MEAN DEVIATION= 14.597	MEAN DEVIATION= 22.271	MEAN DEVIATION= 14.915	MEAN DEVIATION= 22.327	MEAN DEVIATION= 18.750

ABSOLUTE X-COORDINATE(S)

ABS. Y COOR.		.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5	14.5	15.5	16.5	17.5	18.5	19.5
17.5	N	72.9	75.2	76.5	79.6	83.9	89.6	96.3	97.5	100.6	101.6	101.5	100.2	98.3	93.7	89.8	84.8	78.9	75.5	75.5	72.5
	E	39.1	41.8	49.4	55.6	63.6	69.3	75.7	79.8	83.6	84.7	83.6	82.9	81.8	82.2	83.1	84.9	86.9	85.7	78.6	71.5
	S	53.4	42.3	33.3	29.3	29.4	31.1	33.6	35.5	37.4	38.1	37.9	37.2	35.7	33.5	31.3	29.6	29.2	32.6	41.2	51.4
	W	71.7	79.8	85.9	86.6	85.0	82.9	82.0	81.7	82.7	83.6	83.9	83.1	79.5	75.3	69.6	64.2	55.7	48.8	42.2	39.7
16.5	N	78.2	79.6	80.4	83.3	87.8	93.6	98.9	102.6	106.5	107.9	107.5	106.0	103.2	98.4	93.7	89.2	82.3	79.6	79.5	76.2
	E	31.0	32.4	37.9	44.5	51.5	56.2	59.8	62.5	64.6	64.5	64.0	63.7	62.5	63.4	66.6	70.7	77.4	78.8	73.7	65.7
	S	61.7	53.3	44.5	40.3	40.5	43.1	46.3	48.8	51.2	51.7	51.5	51.1	49.0	45.6	43.2	41.2	39.6	43.3	52.7	59.0
	W	66.1	75.5	79.5	77.3	70.9	66.1	63.1	62.3	63.3	63.6	64.1	64.3	62.3	59.4	56.7	52.0	44.5	37.8	33.5	31.1
15.5	N	86.7	83.6	81.6	80.9	85.8	91.9	98.3	102.9	108.0	109.4	108.5	106.5	104.3	98.0	92.2	87.0	80.0	82.2	83.4	82.7
	E	26.2	27.4	32.4	38.1	44.2	47.3	49.7	50.9	52.2	52.1	51.2	50.2	49.1	50.1	53.1	60.3	68.4	73.6	66.4	59.3
	S	71.1	65.3	59.7	55.6	57.3	59.9	64.1	67.3	71.0	71.5	72.1	71.2	68.7	63.8	60.7	57.6	56.3	59.7	64.2	67.6
	W	60.0	69.7	73.6	69.4	60.6	53.0	49.7	48.8	50.1	51.1	51.7	51.4	50.7	49.6	47.4	44.8	37.9	32.7	27.7	26.1
14.5	N	88.3	79.9	71.6	67.1	71.2	76.4	83.0	88.1	91.6	93.1	92.4	90.7	89.1	83.2	76.7	72.1	67.5	70.8	78.6	83.2
	E	28.9	30.1	35.7	41.6	49.2	52.1	55.2	57.2	58.2	57.8	57.1	55.6	54.8	55.9	59.1	65.7	76.9	78.6	72.5	64.9
	S	78.2	72.6	67.1	64.5	65.9	69.2	75.1	79.2	82.9	83.8	82.9	81.4	79.6	75.5	69.7	67.5	65.9	67.4	72.2	76.4
	W	65.5	75.5	80.0	75.9	66.3	58.8	55.3	54.7	55.3	56.4	57.7	57.8	56.5	55.0	52.0	49.1	42.4	35.5	30.5	29.0
13.5	N	84.6	70.7	56.9	48.8	51.0	55.5	51.4	64.3	68.3	69.2	69.3	68.0	65.2	60.4	55.8	52.7	48.5	56.2	69.1	80.5
	E	41.1	44.1	51.4	60.5	69.5	76.1	83.5	87.4	90.9	91.1	90.2	88.8	87.0	86.1	90.3	97.3	103.3	102.4	94.0	83.1
	S	84.5	76.8	68.3	63.9	64.7	68.4	74.2	77.4	82.1	83.1	83.2	82.2	79.2	73.5	69.3	67.1	63.4	67.4	76.1	81.3
	W	83.4	97.0	104.4	103.1	96.9	90.3	86.8	85.9	88.0	89.3	91.0	90.7	87.3	82.4	76.2	71.2	60.2	51.1	45.2	41.4
12.5	N	82.6	65.3	48.9	41.0	41.7	45.7	50.3	53.7	57.1	58.1	57.6	56.5	54.7	50.0	46.5	42.8	40.8	48.2	65.0	78.3
	E	53.8	57.8	67.6	77.4	89.0	98.3	109.3	117.0	122.6	124.7	122.8	121.3	119.1	119.8	121.8	124.2	126.3	122.4	110.6	98.4
	S	85.8	72.0	57.8	51.5	52.3	55.8	61.3	65.1	69.0	70.7	69.7	68.2	65.9	61.8	57.1	53.8	51.5	57.5	72.2	81.9
	W	99.3	114.0	124.1	127.6	124.0	120.4	119.4	119.3	120.6	122.8	123.8	121.7	116.1	108.5	99.9	90.0	77.4	67.1	59.0	53.9
11.5	N	82.2	69.0	54.8	45.3	48.8	52.3	57.1	60.4	64.7	65.2	64.7	63.5	61.5	57.2	52.9	50.5	68.1	54.4	58.8	78.7
	E	56.1	60.6	70.0	81.1	92.7	103.9	114.2	121.5	129.2	130.2	128.3	126.7	125.5	125.8	126.9	129.9	132.5	126.9	115.0	101.8
	S	88.4	71.5	54.5	46.2	47.3	51.0	56.4	60.4	65.2	65.5	65.0	63.6	61.6	57.0	51.4	49.3	46.2	54.4	70.9	86.3
	W	102.4	118.0	128.9	133.4	130.2	126.8	124.9	124.8	127.7	128.3	129.6	127.3	121.0	114.4	104.3	94.2	81.0	69.9	60.9	56.2
10.5	N	88.2	79.6	69.2	64.6	55.6	69.6	75.6	80.0	84.3	85.3	84.7	83.7	81.6	75.6	70.4	68.0	64.3	68.5	78.2	84.4
	E	47.2	50.7	59.8	69.5	81.0	88.3	96.2	101.6	105.7	106.3	105.3	104.2	102.4	102.1	105.3	110.4	117.9	116.8	105.5	92.6
	S	93.1	78.7	63.7	55.7	57.8	61.9	67.8	72.6	77.2	78.3	78.0	77.2	74.6	67.8	62.7	59.6	55.4	63.2	77.7	89.1
	W	92.9	108.5	117.6	117.7	111.4	104.5	101.3	101.8	103.5	104.6	105.7	105.3	102.1	96.1	88.9	81.8	69.0	59.5	51.5	47.8
9.5	N	97.5	90.2	81.0	76.6	78.3	84.1	91.0	96.2	101.9	102.6	102.3	100.6	97.8	91.4	85.2	80.8	75.8	80.8	88.7	93.6
	E	38.6	41.0	49.1	57.3	56.9	72.1	76.9	80.4	82.8	82.3	81.9	80.6	78.7	78.4	81.7	90.9	100.4	102.6	94.5	81.6
	S	98.5	89.1	77.9	71.9	74.0	79.7	86.0	91.8	97.4	98.2	98.5	96.8	93.4	86.4	80.4	75.9	71.0	77.5	87.9	94.9
	W	82.9	97.4	104.7	101.5	90.2	81.5	77.6	77.5	79.9	80.5	82.5	82.6	80.7	76.4	72.3	67.9	56.6	49.1	41.8	39.4
8.5	N	98.8	89.2	78.6	72.5	74.9	80.6	87.1	92.9	97.9	99.4	99.6	97.1	94.2	87.5	81.4	76.6	71.8	78.4	88.5	95.2
	E	38.6	40.7	48.9	57.3	57.2	72.1	76.7	80.1	82.9	82.4	82.0	80.2	78.5	78.4	81.7	90.9	100.5	102.6	94.5	81.5
	S	96.7	89.6	80.6	76.1	77.6	83.4	90.0	95.1	100.4	101.8	101.9	99.4	96.9	90.3	84.1	79.8	75.0	80.3	88.3	92.8
	W	82.9	97.6	104.9	101.7	90.3	81.5	77.7	77.3	79.2	80.8	82.9	82.5	80.5	76.4	72.3	67.7	56.7	48.9	41.8	39.4
7.5	N	94.0	79.5	64.5	56.5	57.4	62.2	67.9	72.4	77.3	78.8	78.5	77.2	74.1	68.2	63.5	59.1	56.1	64.2	78.4	90.0
	E	47.6	50.4	58.7	68.9	79.2	87.6	94.6	99.6	104.6	105.7	104.1	102.7	100.7	101.0	104.4	108.9	117.4	116.4	105.2	91.5
	S	88.2	79.3	69.0	63.8	64.4	69.3	74.3	78.1	82.7	84.3	83.6	82.0	79.7	74.6	70.1	66.1	63.5	68.5	78.0	84.4
	W	92.7	108.0	116.9	117.1	109.7	103.9	100.2	99.6	101.6	103.8	105.3	104.3	100.0	94.4	88.4	79.7	68.4	58.5	51.1	47.9
6.5	N	88.9	72.3	54.8	46.5	47.7	51.4	56.1	60.3	65.1	65.7	64.8	63.9	61.7	56.6	51.7	49.3	46.6	54.5	71.1	86.8
	E	56.0	60.9	69.9	80.9	93.4	103.5	113.4	120.8	128.4	129.5	128.3	127.0	125.1	125.7	127.0	129.8	133.2	128.2	114.9	101.6
	S	81.9	68.7	54.0	47.5	48.6	51.8	55.8	59.1	63.2	63.4	63.3	62.2	59.9	56.2	52.0	49.8	47.5	53.6	67.7	78.2
	W	102.6	118.3	129.1	133.0	130.9	127.1	124.5	124.7	127.0	127.5	129.1	127.3	120.4	113.7	103.7	93.4	80.9	69.8	61.1	56.3
5.5	N	85.5	72.3	57.5	51.0	52.1	55.1	50.9	65.0	68.7	70.2	69.5	67.9	65.5	61.5	55.7	53.4	51.1	57.3	71.7	81.5
	E	53.6	58.3	66.6	77.2	88.3	97.2	108.5	116.0	122.0	123.8	122.1	120.4	118.2	119.0	119.9	123.7	125.9	122.4	110.0	98.1
	S	82.1	65.7	49.8	40.5	41.3	44.3	50.1	53.1	56.3	57.3	56.6	55.5	54.0	50.0	45.5	42.6	40.2	47.9	66.7	78.0
	W	99.4	114.0	124.0	127.2	123.8	118.9	118.7	119.0	120.1	122.1	123.1	121.0	115.1	108.1	97.8	88.5	77.1	66.0	58.2	53.4
4.5	N	83.8	76.3	67.5	63.7	64.2	68.2	74.3	77.8	82.2	82.9	82.9	81.0	79.3	72.8	68.5	65.5	63.8	66.8	75.4	79.8
	E	40.6	43.1	50.4	59.1	68.0	74.3	81.4	85.4	88.8	88.8	87.9	85.7	85.1	84.2	88.2	94.0	101.6	100.7	92.4	81.7
	S	84.6	70.6	56.9	49.4	50.7	55.2	61.1	64.2	68.2	69.1	68.6	67.1	65.6	60.2	55.4	52.1	48.8	56.0	69.4	80.1
	W	82.8	95.2	102.9	102.0	94.2	88.2	85.1	84.0	85.9	87.4	88.7	88.0	85.3	80.0	74.2	68.5	58.9	50.1	43.8	40.7
3.5	N	77.6	72.5	66.9	63.3	65.7	68.9	74.9	78.6	82.5	83.5	82.7	81.2	79.3	75.2	69.2	67.5	65.0	67.4	71.3	73.7
	E	29.1	30.2	35.1	40.5	46.9	51.4	54.6	56.2	57.7	57.5	56.6	55.4	54.6	55.5	58.6	65.4	75.6	78.8	72.4	64.6
	S	89.1	82.0	73.6	67.0	72.1	77.9	83.8	88.7	93.3	94.6	93.6	92.2	89.8	84.0	77.7	72.7	67.8	72.5	80.0	86.7
	W	65.5	75.6	80.2	74.5	66.2	58.5	55.0	54.2	55.2	56.2	57.2	57.3	56.1	54.3	51.2	48.9	41.1	34.8	30.6	29.1
2.5	N	70.8	65.4	57.4	55.5	56.8	59.5	63.7	66.7	70.5	70.7	71.3	70.4	68.6	63.2	60.6	57.4	55.7	58.6	63.4	67.2
	E	26.5	27.9	31.5	37.7	44.3	47.1	49.7	50.7	52.1	51.8	51.1	50.0	49.4	50.2	53.3	60.7	69.0	72.9	66.9	59.3
	S	88.3	86.9	82.6	83.5	98.6	94.0	100.4	104.9	110.2	111.4	110.6	108.4	106.4	100.5	94.0	89.4	82.2	83.7	85.9	85.5
	W	60.2	70.1	72.3	70.2	60.9	53.2	49.8	48.8	50.1	51.1	51.4	51.1	50.7	49.4	47.1	44.8	37.3	32.2	27.9	26.4
1.5	N	62.0	53.4	44.5	40.5	40.6	43.1	46.9	49.4	51.1	51.5	51.1	50.8	49.2	45.9	42.7	40.8	39.6	43.2	51.8	58.4
	E	31.9	33.7	38.6	45.4	52.5	57.0	61.0	63.5	65.3	65.8	65.1	64.8	64.1	64.0	67.1	73.0	79.1	79.4	74.2	65.7
	S	78.9	82.9	83.0	85.4	89.4	94.9	100.1	103.6	107.7	108.7	108.4	106.8	104.3	100.0	95.2	90.8	84.1	81.9	81.8	77.8
	W	66.3	76.3	81.1	80.2	72.9	67.6	64.6	63.7	64.1	64.9	65.2	65.2	63.4	60.0	56.8	53.2	44.5	38.2	33.9	31.7
.5	N	51.9	42.6	33.5	29.3	29.2	30.9	33.4	35.2	36.9	37.7	37.5	36.7	35.4	33.2	31.0	29.3	28.9	32.7	41.6	51.5
	E	39.8	44.8	51.6	58.0	66.4	72.1	79.0	82.9	86.5	87.8	87.0	86.3	85.2	86.0	87.2	89.4	91.5	89.8	81.4	72.9
	S	71.9	76.7	77.6	80.1	84.4	90.0	94.5	97.7	100.7	102.2	101.7	100.2	98.0	93.8	89.8	85.4	79.5	76.5	76.3	72.6
	W	71.1	81.9	89.4	91.4	89.6	87.0	86.0	85.3	85.9	86.7	87.2	86.2	82.7	78.2	72.2	66.7	57.9	51.0	44.8	41.7

Figure D-4 ESI Using Uniform Luminaire Layout

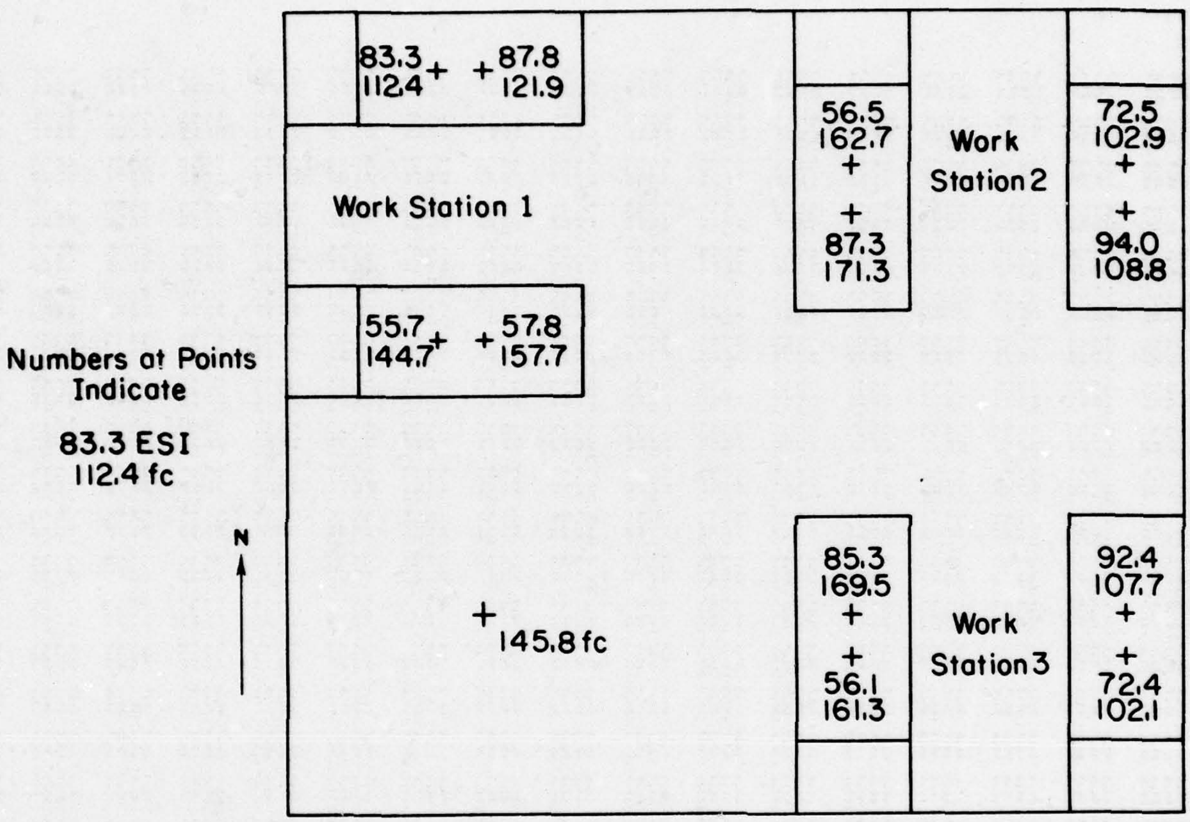


Figure D-5 ESI and Illumination for Uniform Lighting Layout

In order to reduce the lighting load, the layout of Fig. D-6 is analyzed. The ESI, illumination, and VCP of the Lumen II output are shown in Figs. D-7, D-8, and D-9 respectively. Fig. D-6 also shows ESI and illumination levels at the same points as in the analysis of the uniform layout. Note that the ESI levels in general are higher while the illumination levels are lower. Also, note that in the south-west corner where no tasks are being performed the illumination has been lowered from 146 fc to 35 fc. There are 736 watts of lighting installed in the layout of Fig. D-6.

To determine which system - uniform or task - is most economical a secondary economic analysis is performed. The analysis on the following pages shows that system B - the task lighting layout - has the lower present value and thus is the more economical.

It is important to note that the economic analysis assumed that the visibility under both layouts had equal value. As was said before, the ESI's are higher with the task layout than with the uniform layout. Higher ESI levels and therefore, better visibility will probably increase worker productivity. Higher productivity is a savings to the cost of installing a good lighting system. When current research establishes factors which relate productivity to visibility, the costs (savings?) can be included in the economic analysis. Also included is Fig. D-10 which is a contour plot of the ESI's looking west for the task lighting layout.

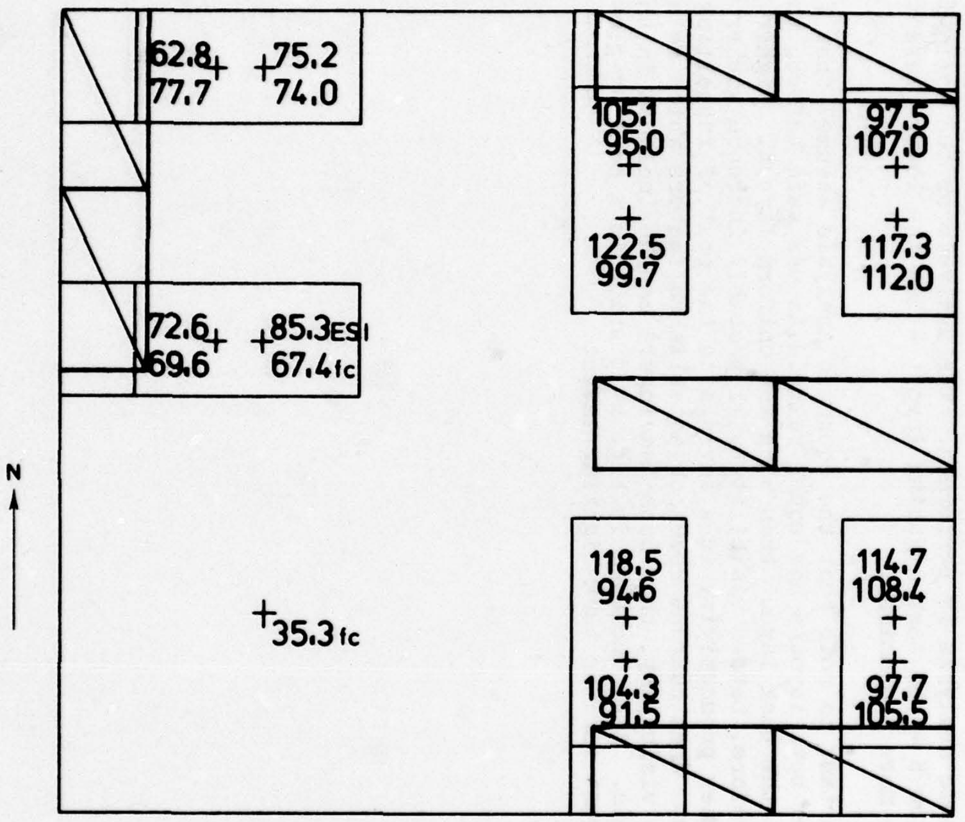


Figure D-6 Task Lighting

EQUIVALENT SPHERE ILLUMINATION

TARGET DESCRIPTION: PENCIL TARGET - CONCENTRIC RINGS @ 25 DEGREE VIEWING ANGLE
SPHERE CONTRAST: .1675

WORKING PLANE HEIGHT 2.50

NORTH	EAST	SOUTH	WEST	TOTAL:
AVERAGE= 40.360	AVERAGE= 58.421	AVERAGE= 49.070	AVERAGE= 51.054	AVERAGE= 50.501
MINIMUM= 8.926	MINIMUM= 10.789	MINIMUM= 11.077	MINIMUM= 10.573	MINIMUM= 8.926
MAXIMUM= 96.530	MAXIMUM= 117.316	MAXIMUM= 103.189	MAXIMUM= 126.282	MAXIMUM= 126.282
MEAN DEVIATION= 17.789	MEAN DEVIATION= 19.832	MEAN DEVIATION= 18.435	MEAN DEVIATION= 25.572	MEAN DEVIATION= 20.366

ABS. Y COOR.		.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5	14.5	15.5	16.5	17.5	18.5	19.5
17.5	N	33.4	33.6	49.9	66.1	75.0	77.3	79.2	76.7	70.3	66.3	59.3	55.6	52.1	49.4	49.4	51.0	49.8	49.1	49.0	49.0
	E	34.8	47.9	61.1	61.9	57.4	52.8	45.4	33.0	20.5	12.7	10.8	11.2	13.4	16.9	20.1	21.5	24.3	29.6	36.4	42.9
	S	11.1	11.8	20.3	33.1	50.0	62.5	71.0	75.6	72.5	69.6	61.0	53.6	46.5	42.5	41.8	43.3	41.7	41.0	40.4	41.0
	W	44.5	30.4	20.1	13.9	13.7	17.5	22.1	27.9	30.7	35.0	40.9	45.5	43.4	37.4	30.4	25.4	22.3	21.0	18.7	15.9
16.5	N	28.0	28.2	43.0	62.8	75.2	80.9	83.5	81.8	74.8	67.9	57.6	49.0	39.2	34.7	33.8	35.8	34.2	33.8	34.8	37.4
	E	34.6	50.8	66.0	67.2	60.6	54.4	47.3	34.7	22.6	15.5	12.8	13.9	18.1	21.5	25.5	27.9	31.4	37.3	44.7	52.0
	S	13.0	14.0	23.7	38.7	56.9	70.6	80.1	84.1	81.7	77.5	71.2	68.2	64.0	60.8	61.3	64.2	61.2	60.5	59.4	57.1
	W	44.9	29.9	18.4	12.4	12.1	15.9	21.2	28.1	34.0	40.6	49.5	56.6	55.3	48.8	39.1	33.3	28.5	26.3	23.6	19.6
15.5	N	22.7	23.1	37.0	50.4	74.5	83.7	87.9	89.3	83.5	75.1	60.3	45.0	32.9	26.3	28.7	27.1	26.0	26.4	26.2	30.2
	E	35.6	52.9	70.4	71.9	66.0	59.3	54.0	42.1	30.7	23.6	22.9	25.4	31.0	36.1	42.6	48.0	54.5	62.6	68.9	75.6
	S	14.7	16.4	26.3	42.6	63.4	77.1	86.7	92.4	90.5	85.0	77.6	73.7	69.0	64.3	65.2	67.1	65.8	65.5	63.0	62.0
	W	45.5	29.3	17.7	11.6	11.4	14.0	21.1	31.1	41.7	55.3	67.5	78.1	80.8	75.5	65.2	58.6	50.4	45.5	38.8	33.3
14.5	N	18.9	20.0	33.2	53.9	72.8	83.1	90.3	92.6	87.8	81.0	63.5	43.4	29.8	22.3	21.4	23.1	22.2	21.6	22.2	26.5
	E	36.3	54.6	72.0	74.6	70.3	63.5	60.7	50.6	40.2	35.8	37.1	42.3	51.3	59.8	68.5	77.1	86.4	92.7	97.5	100.1
	S	16.7	17.6	29.3	48.7	69.1	82.9	92.8	97.0	94.6	90.0	77.6	67.7	57.9	52.0	50.1	53.9	51.6	50.7	50.2	51.7
	W	46.0	29.4	17.2	11.2	10.9	13.6	22.1	34.1	49.6	68.8	84.1	99.0	105.1	105.5	97.2	91.4	80.9	72.8	63.4	55.1
13.5	N	16.8	18.8	30.1	49.0	68.5	82.3	91.3	94.5	90.1	82.9	67.5	46.9	31.6	23.7	22.7	24.6	23.0	23.3	23.8	28.8
	E	37.1	55.5	74.0	78.6	73.6	68.5	68.1	59.8	50.6	47.6	52.8	60.9	71.7	81.1	91.8	102.4	110.2	115.6	117.3	115.0
	S	18.5	20.8	35.6	57.7	77.9	91.1	99.9	103.2	100.3	93.6	80.3	61.9	45.4	35.5	34.4	36.8	34.2	35.0	35.5	40.5
	W	47.1	29.9	17.9	11.6	11.3	14.2	23.3	37.3	55.8	77.0	95.9	113.2	122.5	126.3	120.3	119.4	105.0	95.5	86.8	75.7
12.5	N	14.8	16.7	26.8	43.5	63.0	78.1	88.3	93.3	91.4	85.1	71.4	54.6	40.5	31.7	31.2	32.8	31.5	31.2	31.6	35.8
	E	35.4	52.5	70.7	72.8	68.4	63.8	63.9	56.4	49.0	46.5	50.7	57.9	69.2	78.9	89.9	98.8	106.8	112.5	114.9	113.5
	S	22.1	23.4	39.3	62.2	79.1	90.4	97.7	100.0	95.9	88.2	70.8	49.4	33.6	28.3	24.3	25.6	24.5	24.5	25.2	30.2
	W	44.2	28.1	16.7	10.9	10.6	13.8	23.2	36.9	54.6	76.0	93.3	109.3	118.8	121.5	118.3	114.1	102.0	93.6	84.0	74.2
11.5	N	12.9	13.6	23.3	38.9	58.7	76.4	86.1	90.5	91.0	85.9	74.8	65.8	55.2	49.9	48.1	50.6	48.8	48.5	48.9	49.6
	E	36.5	53.8	68.8	72.3	67.8	63.6	61.7	52.5	46.9	41.1	41.8	47.9	56.7	66.2	75.0	84.5	93.7	100.2	106.1	108.4
	S	29.1	30.9	48.6	70.1	84.8	93.2	98.9	100.0	98.9	89.0	70.7	49.7	33.5	25.8	23.9	26.0	24.7	24.6	25.3	29.8
	W	43.5	28.4	17.5	11.8	11.8	16.5	25.5	39.8	59.6	79.6	94.2	109.7	113.1	115.7	105.4	99.5	87.9	77.8	70.2	61.7
10.5	N	10.8	11.6	20.2	34.8	54.6	68.2	81.2	87.2	88.9	81.2	74.8	70.7	68.2	62.4	60.7	64.9	62.3	61.0	60.5	59.2
	E	38.0	51.8	68.6	72.9	72.3	64.9	62.7	50.6	38.9	29.3	28.5	31.0	37.9	42.3	50.2	56.8	63.9	71.7	80.3	86.7
	S	33.4	35.1	52.5	72.6	85.3	88.7	94.6	95.4	92.3	81.1	68.1	52.3	39.8	30.8	28.9	31.3	29.6	29.4	29.8	33.8
	W	42.6	29.6	20.3	14.4	16.1	20.4	29.1	41.2	54.7	66.9	81.4	92.5	96.0	87.6	74.4	68.0	58.9	52.2	46.4	39.5
9.5	N	9.0	9.7	17.0	30.1	46.5	61.4	72.1	78.4	80.3	76.7	68.6	63.9	59.8	55.2	54.9	57.8	55.3	55.2	54.0	53.0
	E	40.9	52.0	64.6	69.1	68.8	63.8	58.7	44.8	30.3	20.8	18.1	19.3	23.0	26.7	31.2	34.3	38.4	45.4	54.9	63.4
	S	34.2	36.0	52.5	69.7	77.8	80.5	82.8	84.6	82.7	77.1	67.1	57.2	48.7	41.7	41.0	43.7	41.9	41.7	41.8	42.9
	W	42.6	32.3	24.9	21.1	21.5	25.2	31.0	39.3	46.6	53.0	63.6	70.7	68.3	59.0	47.4	40.9	35.0	33.2	29.5	25.2
8.5	N	8.9	9.5	16.5	28.6	43.7	57.3	68.2	74.9	77.4	75.6	67.4	56.8	49.7	42.5	41.6	44.1	42.1	42.5	42.5	42.9
	E	45.0	52.3	62.0	67.3	70.3	65.8	60.1	46.3	31.3	21.3	18.5	19.2	23.2	26.9	31.3	34.3	38.5	45.3	54.8	63.4
	S	29.6	31.9	47.0	64.7	70.1	73.2	75.6	77.1	78.4	75.8	67.9	61.2	59.0	54.0	53.7	56.7	54.3	55.0	54.1	52.1
	W	42.9	36.5	32.1	29.4	30.2	33.1	37.3	43.1	47.5	54.5	64.7	70.0	68.7	59.1	47.3	40.7	34.8	33.2	29.9	25.5
7.5	N	10.9	11.4	18.9	30.4	42.9	56.9	68.0	75.2	80.9	79.0	68.4	53.3	39.0	30.9	31.0	32.2	30.9	31.3	31.4	35.8
	E	49.2	51.1	59.4	65.1	66.1	65.0	60.5	49.9	40.0	32.1	29.7	32.0	37.0	42.5	51.3	56.2	63.8	72.2	79.3	87.0
	S	25.6	26.8	41.2	57.1	62.7	66.4	70.1	74.3	77.8	76.7	69.9	66.2	62.8	59.1	60.2	62.1	59.8	60.3	59.2	58.2
	W	42.1	37.6	36.5	36.0	36.2	41.0	46.3	53.5	61.1	73.9	84.7	94.4	92.4	85.4	75.7	66.3	58.0	51.9	46.0	40.2
6.5	N	14.3	16.2	22.8	32.3	43.5	54.9	65.1	72.3	80.1	78.0	66.0	47.3	33.0	25.0	24.0	26.5	25.5	24.8	29.4	30.1
	E	44.9	47.6	53.9	57.5	59.9	58.6	57.6	51.5	48.2	44.1	44.4	49.0	57.2	66.0	78.2	84.5	94.7	100.7	109.3	108.3
	S	23.7	25.4	35.5	47.5	54.4	57.9	61.6	67.4	74.1	72.2	66.4	59.1	50.9	46.3	45.7	48.9	47.3	46.7	46.7	47.6
	W	37.9	36.0	36.6	35.7	36.2	40.2	48.0	50.4	69.9	81.9	95.7	108.0	112.5	113.1	103.7	98.4	88.1	77.2	69.2	61.0
5.5	N	18.7	19.5	24.6	32.0	40.6	49.0	59.3	67.9	74.1	74.2	63.7	44.8	31.7	24.0	22.8	24.8	23.8	24.0	24.7	29.7
	E	38.5	39.6	43.8	47.5	49.8	48.8	50.8	50.3	49.8	50.2	53.1	59.5	69.9	79.4	89.4	98.7	106.8	112.5	114.5	113.1
	S	22.5	24.2	31.6	41.8	44.7	47.6	55.7	63.7	70.7	71.8	63.2	49.2	37.8	30.0	29.4	31.8	30.4	30.5	30.9	35.0
	W	31.6	30.2	30.9	30.3	30.9	33.9	42.0	54.0	66.0	81.0	94.4	108.9	117.4	120.9	114.9	112.1	101.1	92.0	83.0	73.4
4.5	N	22.9	24.0	28.6	34.4	41.2	48.1	58.8	65.5	74.3	75.5	69.1	53.5	41.1	32.5	31.7	34.3	33.3	32.9	33.5	37.6
	E	34.3	35.5	39.9	42.5	44.4	44.1	47.5	47.8	49.3	50.7	53.9	59.9	70.6	79.6	89.4	99.3	107.4	112.5	114.7	112.6
	S	22.1	23.4	28.8	35.0	38.1	41.4	49.6	57.2	65.9	66.8	58.8	40.9	29.7	22.2	21.6	23.6	22.5	22.6	23.0	27.5
	W	27.5	27.0	28.2	28.0	28.5	31.9	40.2	50.6	64.3	78.6	92.9	107.6	118.5	119.8	114.5	112.8	101.2	92.1	83.0	73.6
3.5	N	24.6	25.7	28.5	32.6	38.4	44.4	53.0	60.1	69.1	72.4	68.2	61.2	54.1	49.3	47.9	51.9	50.2	49.8	48.7	50.4
	E	31.2	32.0	34.7	36.1	38.7	39.0	39.6	39.3	39.4	39.3	39.7	44.6	52.5	60.7	69.3	78.1	86.3	93.0	97.7	100.1
	S	22.5	24.0	26.6	29.6	33.6	37.5	43.7	53.0	62.7	64.5	54.8	38.5	27.4	20.9	20.3	22.0	21.3	21.2	21.7	25.9
	W	24.1	23.8	24.7	24.0	25.5	29.3	36.1	45.2	58.1	71.6	84.5	97.7	104.3	103.2	95.0	90.2	79.0	70.8	63.3	54.6
2.5	N	24.7	26.1	27.7	32.3	36.9	41.0	49.3	55.5	65.1	66.6	67.0	65.3	64.7	60.9	62.6	64.6	64.5	63.9	61.4	60.6
	E	28.2	29.4	30.9	33.4	35.3	34.5	34.7	31.9	29.5	25.8	24.5	26.5	32.0	37.1	43.5	49.4	55.4	62.3	69.2	75.5
	S	21.8	23.0	24.3	27.9	31.1	33.6	39.8	46.0	57.4	57.9	51.7	39.3	30.6	24.7	24.4	26.0	25.5	25.5	25.6	29.6
	W	21.6	21.0	21.9	23.4	24.0	27.7	32.5	38.1	45.4	56.2	67.9	75.7	79.2	74.0	63.8	57.2	49.6	44.1	38.7	32.9
1.5	N	25.4	26.1	28.3	31.8	34.4	38.5	44.9	51.1	57.7	60.4	59.8	58.9	57.7	56.1	56.2	59.1	58.0	57.9	55.9	53.8
	E	27.1	27.7	29.7	31.5	32.1	31.3	30.5	26.5	21.5	16.9	13.7	14.5	18.4	22.0	25.7	28.2	31.3	36.7	43.6	51.4
	S	20.9	21.9	23.3	25.7	26.9	30.1	34.8	40.8	46.5	50.3	48.5	41.4	36.7	33.3	32.8	34.8	34.1	34.3	34.6	36.6
	W	21.2	21.1	22.0	23.5	24.7	26.8	29.4	32.2	34.1	38.7	46.7	53.6	53.6	46.1	36.8	32.1	27.6	26.1	23.3	19.4
.5	N	24.1	25.9	28.1	29.9	33.2	36.2	42.0	47.1	53.8	56.2	53.4	48.9	43.5	41.1	40.6	42.4	41.5	41.3	41.0	41.0
	E	24.8	26.7	28.5	29.0	30.3	29.1	28.5	23.7	19.5	13.9	11.9	12.3	14.3	18.3	21.5	23.0	25.8	31.5	38.5	44.9
	S	19.9	21.4	23.3	24.2	26.2	28.7	33.2	38.6	43.0	48.4	48.7	47.8	47.1	45.4	46.0	49.3	48.3	48.0	47.9	47.6
	W	19.7	20.6	21.0	22.5	24.2	25.4	28.0	29.1	31.1	34.2	41.0	46.6	44.5	38.2	30.7	25.7	22.8	21.6	19.2	16.1

Figure D-7 ESI Using Task Oriented Lighting

ILLUMINATION

WORKING PLANE HEIGHT 2.50

AVERAGE 77.624 MINIMUM 22.488 MAXIMUM 121.852 MEAN DEVIATION 23.140

ABS. Y COOR.	.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5	14.5	15.5	16.5	17.5	18.5	19.5
17.5	75.9	73.0	74.6	71.3	68.1	64.0	60.9	59.0	57.4	60.6	66.1	74.4	85.1	93.3	99.6	104.0	103.5	100.0	95.1	87.5
16.5	83.5	81.2	81.8	77.7	74.0	68.8	65.4	62.7	61.0	63.7	69.4	79.2	90.2	98.8	105.4	111.2	109.9	107.2	102.4	92.0
15.5	88.5	85.1	85.5	81.0	77.1	71.7	67.8	65.4	63.8	66.3	71.8	81.3	92.8	102.0	108.0	113.7	112.5	110.7	104.1	95.2
14.5	90.9	87.1	87.2	82.6	79.0	73.5	69.8	67.3	65.7	69.1	74.1	83.8	95.0	103.6	110.1	116.3	115.3	112.3	107.0	98.1
13.5	91.7	87.9	88.4	84.0	80.5	75.3	71.9	69.7	68.9	72.3	78.6	88.5	99.7	108.5	115.0	121.9	119.7	117.5	112.0	103.0
12.5	86.8	82.9	83.7	79.5	76.1	71.8	68.8	67.3	66.5	70.1	75.9	86.5	97.1	108.6	112.6	118.2	116.9	116.6	109.2	100.5
11.5	81.4	77.9	76.8	75.4	73.1	68.0	67.0	65.5	66.6	70.0	76.2	86.5	97.4	107.0	113.0	119.2	117.9	115.5	110.6	101.7
10.5	72.6	69.5	71.9	69.6	67.4	64.2	63.3	62.8	64.2	67.3	74.4	84.7	97.7	105.2	111.5	118.5	117.0	114.2	109.3	100.0
9.5	61.9	59.7	61.5	59.9	58.9	56.9	56.7	57.2	59.0	63.5	70.4	80.7	92.0	100.3	107.2	113.4	112.1	110.2	105.1	96.0
8.5	52.7	51.1	53.2	52.9	52.8	51.8	52.6	53.9	57.0	62.5	70.0	79.9	92.0	100.2	107.0	113.4	111.9	110.4	105.6	96.6
7.5	45.7	43.2	46.6	47.2	47.6	48.3	50.0	52.5	57.4	64.0	72.0	83.0	94.9	103.3	111.0	116.7	115.5	114.0	108.3	99.4
6.5	38.1	37.9	40.9	41.8	43.1	44.1	46.7	50.2	56.6	63.5	72.0	82.9	95.1	104.3	111.0	118.0	116.9	114.2	109.0	100.7
5.5	32.6	32.1	34.8	36.3	37.9	39.1	42.8	47.3	54.0	61.9	70.7	81.7	94.4	103.3	110.3	116.6	115.5	113.4	108.1	99.4
4.5	29.2	29.1	31.0	33.5	35.3	36.9	41.1	45.6	53.2	61.5	70.9	81.7	94.6	103.8	110.5	117.3	115.9	113.8	108.4	100.3
3.5	26.5	26.3	28.6	29.9	32.0	34.1	37.9	42.6	50.2	58.6	67.6	78.7	91.5	100.6	107.5	113.8	113.1	110.8	105.6	96.5
2.5	24.4	24.4	26.1	27.9	30.0	31.6	35.7	40.1	47.4	55.2	64.7	75.7	88.9	97.8	104.9	111.0	110.4	108.3	102.3	93.4
1.5	23.5	23.3	24.9	26.4	27.7	29.5	33.2	37.3	43.7	51.1	60.1	70.7	82.8	91.7	98.5	104.0	103.4	101.6	96.6	87.3
.5	22.5	23.1	24.9	25.6	27.3	28.9	32.8	36.6	42.9	50.7	59.6	70.5	81.5	90.6	97.1	102.6	101.0	99.5	94.4	85.7

Figure D-8 Illumination Using Task Oriented Lighting

VISUAL COMFORT PROBABILITY

VISUAL PLANE HEIGHT 4.00

NORTH	EAST	SOUTH	WEST	TOTAL:
AVERAGE= 80.025	AVERAGE= 77.636	AVERAGE= 83.081	AVERAGE= 85.149	AVERAGE= 81.472
MINIMUM= 67.000	MINIMUM= 64.430	MINIMUM= 64.430	MINIMUM= 64.060	MINIMUM= 64.060
MAXIMUM= 99.990	MAXIMUM= 99.990	MAXIMUM= 99.990	MAXIMUM= 99.990	MAXIMUM= 99.990
MEAN DEVIATION= 6.486	MEAN DEVIATION= 7.967	MEAN DEVIATION= 9.612	MEAN DEVIATION= 6.818	MEAN DEVIATION= 8.208

ABSOLUTE X-COORDINATE(S)

ABS. Y COOR.		.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5	14.5	15.5	16.5	17.5	18.5	19.5
17.5	N	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R
	E	80.2	80.0	79.4	78.8	78.8	79.1	80.0	80.2	81.6	83.9	87.3	90.2	89.8	93.9	97.1	100.0	R	R	R	R
	S	86.9	86.0	83.1	80.8	78.5	76.7	75.8	75.5	75.8	74.5	73.2	72.2	71.6	71.6	71.6	71.2	71.9	73.2	74.2	74.9
	W	R	R	R	R	91.0	76.4	70.9	73.2	77.3	79.7	81.9	83.4	84.6	86.0	87.1	85.8	89.6	87.1	84.4	81.3
16.5	N	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R
	E	78.8	78.2	77.6	77.3	77.0	77.0	77.3	78.2	80.0	82.1	85.3	88.9	88.5	93.1	96.6	100.0	R	R	R	R
	S	89.6	88.5	86.4	84.4	82.4	80.2	78.8	78.5	77.3	75.5	73.6	72.2	70.9	70.5	70.5	70.5	70.9	71.9	72.9	73.6
	W	R	R	R	R	88.9	72.6	67.4	70.5	76.1	78.8	81.1	82.9	84.4	86.0	87.1	85.8	89.4	86.7	83.7	80.2
15.5	N	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R
	E	76.1	75.2	74.2	73.6	73.2	72.9	72.6	73.2	74.9	77.9	81.6	84.9	83.4	90.0	95.3	98.7	R	R	R	R
	S	92.4	91.5	89.6	87.7	85.5	83.7	82.6	80.5	77.9	76.1	74.5	71.6	69.2	68.4	68.1	68.1	68.8	69.5	70.2	71.6
	W	R	R	R	R	86.9	70.5	65.6	69.5	74.9	77.3	79.7	81.6	83.4	85.1	86.4	84.9	88.3	85.1	81.1	76.4
14.5	N	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R
	E	73.9	72.6	71.2	70.5	69.9	69.2	68.8	68.8	70.9	73.9	77.6	81.3	79.1	86.9	93.1	98.0	R	R	R	R
	S	95.1	94.2	92.8	91.0	88.9	87.3	86.0	83.4	80.2	77.6	75.5	72.2	69.2	67.7	67.0	66.6	67.0	68.1	69.2	70.9
	W	R	R	R	R	85.8	68.8	64.4	68.8	73.9	76.1	78.2	80.5	82.4	84.1	85.5	83.7	86.9	82.6	78.2	73.2
13.5	N	100.0	100.0	98.9	98.5	98.2	98.2	98.4	98.3	97.8	96.8	95.3	93.9	92.6	91.0	89.8	89.3	89.4	90.3	91.8	93.3
	E	71.9	70.2	68.8	67.7	67.0	66.3	65.9	66.3	68.1	70.9	74.9	78.8	76.4	84.1	91.0	97.1	R	R	R	R
	S	97.5	96.6	94.5	93.9	92.1	89.8	87.7	85.3	81.6	77.9	75.2	72.2	69.5	67.4	66.3	65.6	65.9	67.0	68.8	70.9
	W	R	R	R	R	85.5	68.4	64.1	68.4	73.2	75.5	77.9	80.0	91.9	83.7	85.1	82.6	85.3	80.5	76.1	70.9
12.5	N	97.2	96.9	96.2	95.3	94.3	93.9	94.3	94.4	92.6	90.2	87.7	84.4	80.5	77.6	76.1	75.2	75.5	77.0	78.8	81.9
	E	70.5	69.2	67.7	66.6	65.9	65.2	64.8	65.6	67.4	70.5	74.2	78.5	76.1	83.9	90.7	96.9	R	R	R	R
	S	98.7	98.1	97.3	96.2	94.7	93.1	91.2	89.1	86.7	83.9	81.3	79.4	77.6	76.4	75.5	74.5	74.9	76.1	77.6	79.1
	W	R	R	R	R	86.4	69.9	64.8	68.4	73.6	76.1	78.5	80.5	82.4	84.1	85.3	82.6	85.3	80.5	76.1	70.5
11.5	N	94.4	94.1	92.5	91.3	90.0	89.4	90.0	89.6	87.9	86.0	84.1	80.0	75.2	72.6	71.6	71.2	71.6	72.6	73.9	77.0
	E	70.5	69.2	67.7	66.6	65.9	65.6	65.9	66.3	68.4	71.9	78.1	80.0	77.6	85.8	92.4	97.7	R	R	R	R
	S	98.8	98.3	97.4	96.1	94.3	92.4	90.2	87.5	84.6	82.1	79.7	77.6	76.4	75.5	74.9	74.2	74.9	76.1	77.6	78.5
	W	R	R	R	R	88.1	71.9	66.3	68.8	74.2	77.0	79.4	81.1	82.6	84.4	85.5	83.1	86.2	81.9	77.3	71.6
10.5	N	91.6	91.2	88.9	87.1	85.8	84.9	84.9	84.6	84.9	83.9	82.6	79.1	75.8	74.2	73.9	74.2	74.5	75.2	76.1	78.2
	E	70.9	69.5	68.4	67.7	67.0	67.4	67.7	68.4	70.5	74.2	78.8	82.6	80.8	88.3	94.3	98.3	R	R	R	R
	S	100.0	100.0	98.7	97.8	96.4	95.1	93.3	90.7	87.9	85.5	83.7	81.6	80.0	79.4	78.5	77.9	78.5	80.0	81.3	82.1
	W	R	R	R	R	90.3	75.5	69.9	71.6	75.8	77.9	80.0	81.6	82.9	84.4	85.3	83.1	86.9	83.1	79.1	73.9
9.5	N	90.0	89.6	87.3	85.1	83.7	82.9	83.1	84.4	85.8	85.1	84.1	82.9	81.6	81.1	81.1	81.1	81.6	82.4	83.4	84.6
	E	71.2	70.5	69.5	68.8	68.4	68.8	69.9	71.6	73.9	76.7	80.8	85.3	84.9	90.5	95.1	98.6	R	R	R	R
	S	100.0	100.0	98.9	98.2	97.1	95.6	93.6	91.0	88.1	85.1	82.4	80.0	77.9	77.0	76.4	75.8	76.1	77.3	78.8	80.0
	W	R	R	R	R	92.4	80.5	75.8	76.4	78.5	80.0	81.6	82.6	83.7	84.9	85.8	83.7	87.5	84.1	80.8	76.4
8.5	N	87.9	87.5	84.6	81.6	80.0	79.7	80.8	82.1	82.6	83.4	83.4	82.9	82.1	82.1	82.1	81.9	82.6	83.7	84.9	85.8
	E	71.2	70.2	69.5	68.8	68.4	68.8	69.5	71.6	73.9	76.7	80.8	85.3	84.9	90.5	95.1	98.6	R	R	R	R
	S	100.0	100.0	100.0	98.7	98.0	96.4	93.8	91.3	88.5	84.9	81.3	78.2	75.8	74.2	73.9	73.6	73.9	74.9	76.1	77.6
	W	R	R	R	R	94.5	85.3	81.9	81.6	81.3	82.4	83.7	84.4	85.1	86.0	86.4	84.1	87.7	84.4	80.8	76.7
7.5	N	85.5	85.1	81.6	78.8	76.7	76.4	77.9	79.7	81.1	81.9	82.4	82.4	82.6	82.9	82.9	82.9	83.7	84.9	86.0	86.7
	E	70.5	69.5	68.4	67.4	67.0	67.0	67.7	68.4	70.5	74.2	78.8	82.4	80.8	88.3	94.2	98.3	R	R	R	R
	S	100.0	100.0	100.0	98.9	98.3	97.2	95.3	91.5	87.5	84.4	81.6	76.4	71.6	69.2	68.4	68.8	69.2	69.5	70.5	73.2
	W	R	R	R	R	96.6	89.1	85.1	84.4	84.9	85.3	85.8	86.2	86.7	87.3	87.7	85.1	87.7	83.7	79.4	73.9
6.5	N	82.6	81.9	78.2	75.2	73.2	72.6	73.2	75.2	77.6	77.9	78.2	78.8	79.4	79.7	79.7	80.0	80.5	81.9	83.1	84.1
	E	70.2	68.8	67.4	66.3	65.9	65.6	66.6	65.9	68.1	71.6	75.8	80.0	77.6	85.5	92.4	97.7	R	R	R	R
	S	100.0	100.0	100.0	100.0	98.7	97.9	96.6	93.5	89.1	84.9	81.6	75.8	69.9	66.3	65.2	64.4	64.6	65.9	67.4	71.2
	W	R	R	R	R	98.2	93.2	89.1	87.7	88.7	88.1	88.1	88.3	88.5	88.9	89.1	86.0	87.5	82.6	77.6	71.9
5.5	N	85.8	84.9	81.6	79.1	77.0	76.1	76.4	77.6	78.8	78.8	78.5	78.2	78.2	77.9	77.6	77.6	78.2	79.4	80.8	82.1
	E	70.2	68.8	67.4	66.3	65.6	64.8	64.4	65.2	67.0	70.2	73.9	78.2	75.8	83.7	90.7	96.9	R	R	R	R
	S	100.0	100.0	100.0	100.0	100.0	98.8	97.9	96.4	93.1	89.1	85.3	80.5	75.5	71.9	69.9	68.4	68.8	70.5	72.9	76.7
	W	R	R	R	R	99.0	96.4	93.6	91.6	91.5	91.2	91.0	90.7	90.5	90.5	90.5	86.9	87.1	81.9	76.7	71.2
4.5	N	85.3	84.4	81.1	77.9	76.1	75.2	74.9	75.2	74.5	74.2	74.2	72.9	71.6	70.5	70.5	70.2	70.9	72.2	73.6	75.5
	E	71.2	69.9	68.4	67.4	66.6	65.6	65.6	65.9	67.7	70.5	74.5	78.5	76.1	83.9	90.8	97.0	R	R	R	R
	S	100.0	100.0	100.0	100.0	100.0	100.0	100.0	99.0	98.2	96.6	94.5	92.4	90.5	88.3	86.4	85.8	85.8	87.1	88.9	91.2
	W	R	R	R	R	100.0	97.9	96.6	95.5	93.9	93.7	93.6	92.8	92.2	92.1	91.9	88.5	88.1	82.6	77.6	71.9
3.5	N	84.9	83.7	80.5	77.6	75.5	74.2	73.9	72.9	71.9	71.2	70.9	69.5	67.7	67.0	67.4	67.4	68.1	69.2	70.2	72.2
	E	73.2	71.9	70.5	69.9	69.2	68.4	68.1	68.4	70.2	73.6	77.0	81.1	78.8	86.4	92.9	97.9	R	R	R	R
	S	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R
	W	R	R	R	R	100.0	98.8	97.9	97.3	96.6	95.9	95.3	94.6	94.1	93.8	93.6	90.7	90.2	85.3	80.2	74.5
2.5	N	84.6	83.4	80.5	77.6	75.5	73.9	72.9	71.2	70.5	69.9	69.5	68.4	67.4	67.4	67.7	68.1	69.2	69.9	70.9	72.2
	E	75.5	74.5	73.6	72.9	72.6	72.2	71.9	72.6	74.2	77.3	81.1	84.4	82.9	89.6	95.1	98.6	R	R	R	R
	S	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R
	W	R	R	R	R	100.0	100.0	98.8	98.4	98.1	97.3	96.6	96.1	95.6	95.3	95.8	97.6	92.1	88.1	83.7	78.2
1.5	N	84.4	83.4	80.8	77.9	75.8	73.6	71.9	70.9	70.2	69.5	68.4	68.4	68.4	68.8	69.5	69.9	70.5	71.9	72.9	73.9
	E	77.9	77.3	76.7	76.4	76.4	76.4	76.4	77.6	79.4	81.6	84.9	88.3	88.1	92.6	96.4	99.0	R	R	R	R
	S	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R
	W	R	R	R	R	100.0	100.0	100.0	99.0	98.8	98.3	97.9	97.4	97.0	96.6	96.2	94.2	93.6	90.2	86.7	82.6
.5	N	84.6	83.7	81.1	78.2	75.5	73.6	71.9	70.9	69.9	69.2	68.8	68.8	68.0	69.5	70.2	70.5	71.6	72.9	74.2	74.9
	E	79.4	79.1	78.5	78.2	77.9	78.5	79.1	79.7	81.1	83.4	86.7	89.8	89.4	93.6	96.9	100.0	R	R	R	R
	S	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R
	W	R	R	R	R	100.0	100.0	100.0	100.0	100.0	99.0	98.8	98.3	97.9	97.6	97.1	95.3	94.4	91.3	88.1	84.4

Figure D-9 VCP Using Task Oriented Lighting

CONTOUR PLOT
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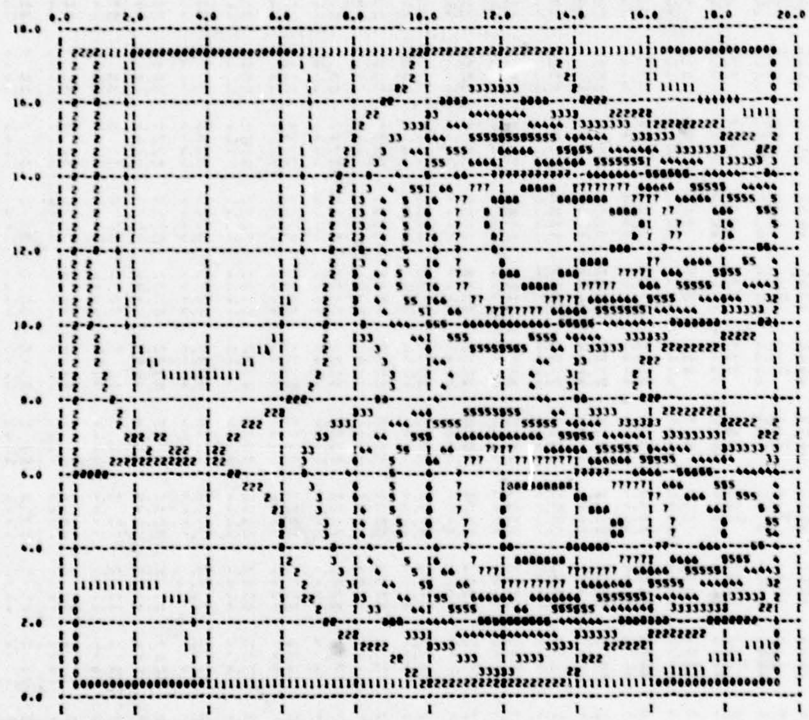
EQUIVALENT SPHERE ILLUMINATION, WEST VIEWING

QUANTITY PLOTTED ESI FOOTCANDLES
SCALE 1 INCH=   2.0 FEET

VALUES	SYMBOL
10.573	0
23.430	1
36.286	2
49.143	3
61.999	4
74.856	5
87.713	6
100.569	7
113.426	8
126.282	9

HORIZONTAL   20 OUT OF 39 HARMONICS USED.
VERTICAL   20 OUT OF 35 HARMONICS USED.



END-OF-FILE ENCOUNTERED, FILENAME -   INPUT

ERROR NUMBER   65   DETECTED BY INPC=   AT ADDRESS 000139
CALLED FROM LUMPLY AT LINE 46

Figure D-10 Contour Plot

SECONDARY ECONOMIC ANALYSIS
SUMMARY OF COSTS
FORMAT A

1. Submitting Department of the Navy Component: __________

2. Date of Submission: __________

3. Project Title: Illuminate 20' x 18' room

4. Description of Project Objective: __________

5. Alternative: System A - uniform 6. Economic Life: 30 years

8. Program/Project Costs					
7. Project Year	a. Non-Recurring Investment	b. Recurring Operations	c. Annual Cost	d. Discount Factor†	e. Discounted Annual Cost
0	1723.40				1723.40
1-30		Electricity	60.72	20.388	1237.96
1-30		Cleaning	90.00	9.891	890.19
6		Relamping	139.20	0.592	82.41
12		Relamping		0.334	46.49
18		Relamping		0.189	26.31
24		Relamping		0.107	14.89
9. TOTALS					4021.65

10a.	Total Project Cost (discounted)	$4021.65	
10b.	Uniform Annual Cost (without terminal value)		
11.	Less Terminal Value (discounted)	-	
12a.	Net Total Project Cost (discounted)	$4021.65	
12b.	Uniform Annual Cost (with terminal value)		

†from NAVFAC P-442, with long-term differential escalation rates from NAVFACINST 4100.6.

SECONDARY ECONOMIC ANALYSIS
SUMMARY OF COSTS
FORMAT A

13. Source/Derivation of Cost Estimates: (Use as much space as required)

a. Non-Recurring Costs:

1.) Research & Development:

2.) Investment:

Initial Installation = $1723.40

b. Recurring Cost(s):

Electricity = $60.72
Cleaning Fixtures = $90.00 per year
Group Relamping = $139.20 each 6 years

c. Net Terminal Value:

None

d. Other Considerations:

14. Name & Title of Principal Action Officer Date

Non-Recurring Costs

Item	Quan.	Material Costs Unit	Material Costs Total	Labor Costs MH	Labor Costs Rate	Labor Costs Total	Line Total
Luminaires	12	$45.60	$547.20	3	$20	$720	$1267.20
Lamps	24	0.80	19.20	-	-	-	19.20
Conduit	100	0.1	10.00	0.13	20	260	270.00
Wiring	300	0.04	12.00	0.01	20	60	72.00
Misc.	1	15.00	15.00	4	20	80	95.00
						Total	$1723.40

Recurring Costs

Operation:

Total Kilowatts = 12 x .092 - 1.104

Burning Hours per year - 2200

Cost per KW-hr = $0.025

Total Energy Cost = $60.72 per year

Maintenance:

Washing Fixtures 30 min. per luminaire at $15.00 per hour

Once each year 12 x 1/2 x 15 = $90.00 per year

Group Relamping - every 6 years

24 x 0.80 = $ 19.20

12 x 0.5 x 20 = 120.00

Total: $139.20 each 6 years with no spot relamping

SECONDARY ECONOMIC ANALYSIS
SUMMARY OF COSTS
FORMAT A

1. Submitting Department of the Navy Component: ____________

2. Date of Submission: ____________

3. Project Title: Illuminate 20' x 18' room

4. Description of Project Objective: ____________

5. Alternative: System B - task   6. Economic Life: 30 years

8. Program/Project Costs					
7. Project Year	a. Non-Recurring Investment	b. Recurring Operations	c. Annual Cost	d. Discount Factor†	e. Discounted Annual Cost
0	1294.60				1294.60
1-30		Electricity	40.48	20.388	825.31
1-30		Cleaning	60.00	9.891	593.46
6		Relamping	92.80	0.592	54.94
12		Relamping		0.334	31.00
18		Relamping		0.189	17.54
24		Relamping		0.107	9.93
9. TOTALS					2826.78

10a. Total Project Cost (discounted) $2826.78
10b. Uniform Annual Cost (without terminal value) ____
11. Less Terminal Value (discounted) -
12a. Net Total Project Cost (discounted) $2826.78
12b. Uniform Annual Cost (with terminal value) ____

†from NAVFAC P-442, with long-term differential escalation rates from NAVFACINST 4100.6.

SECONDARY ECONOMIC ANALYSIS
SUMMARY OF COSTS
FORMAT A

13. Source/Derivation of Cost Estimates: (Use as much space as required)

a. Non-Recurring Costs:

1.) Research & Development:

2.) Investment:

Initial Installation = $1294.60

b. Recurring Cost(s):

Electricity = $40.48 per year
Cleaning Fixtures = $60.00 per year
Group Relamping = $92.80 each 6 years

c. Net Terminal Value:

None

d. Other Considerations:

---

14. Name & Title of Principal Action Officer   Date

Non-Recurring Costs

Item	Quan.	Materials Costs Unit	Materials Costs Total	Labor Costs MH	Labor Costs Rate	Labor Costs Total	Line Total
Luminaires	8	$45.60	$364.80	3	$20	$480	$ 844.80
Lamps	16	0.80	12.80	-	-	-	12.80
Conduit	100	0.1	10.00	0.13	20	260	270.00
Wiring	300	0.04	12.00	0.01	20	60	72.00
Misc.	1	15.00	15.00	4	20	80	95.00
						Total	$1294.6

Recurring Costs

Operation:

Total Kilowatts = 8 (# luminaires) x 0.092 (KW/luminaires) = 0.736

Burning Hours per year = 2200

$/KW-hr = 0.025

Total Energy Cost per year = $40.48

Maintenance:

Washing Fixtures = 8 (# luminaires) x 1/2 (MH/luminaire) x 15 (labor rate)
= $60.00 per year

Group Relamping

16 (# lamps) x 0.80 (material cost/unit) = $12.80 (material)

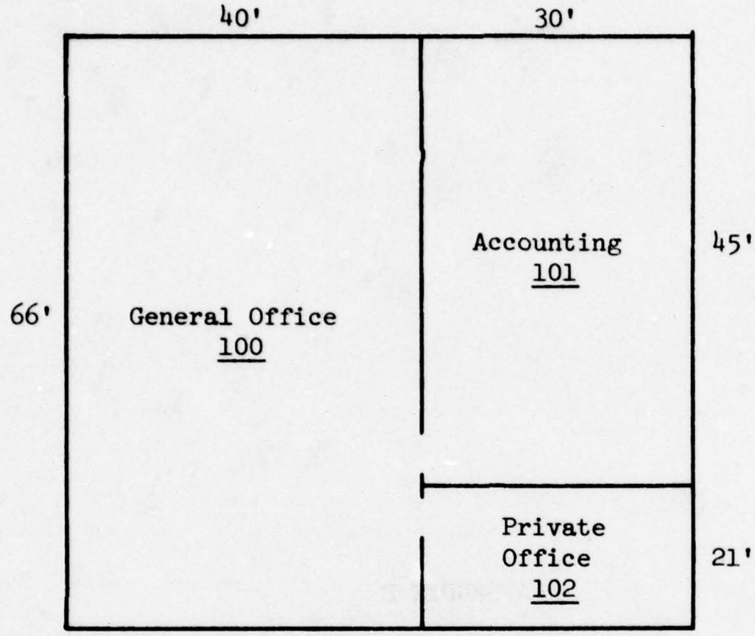
8 (# luminaires) x 0.5 (MH/lamp) x 20 (labor rate) = 80.00 (labor)

Total: $92.80 each 6 years

APPENDIX E

ASHRAE 90-75/EMS-1

POWER BUDGET CALCULATION



$h_{rc} = 5.5$ 80/50/20-Reflectance
Good Color Rendition, Efficacy = 40lms/watt
(Section 3.2.1 - EMS 1)

I. Task Analysis (information obtained from architect, client, or assumed)

General Office - 100

Total Task Locations - 25	E*	# Tasks
T1 - Reading fair reproductions, active filing	100	5
T2 - Medium pencil or ink	70	16
T3 - High contrast printed forms	30	4

Accounting - 101

Total Task Locations - 15		
T1 - Auditing, bookkeeping, ink or medium pencil	150	10
T2 - Intermittent filing	70	5

Private Office - 102

Total Task Locations - 2		
T1 - Ink or medium pencil	70	2

---

*IES Lighting Handbook, 5th Edition, Fig. 9-80.

II. Power Calculation - Longhand

Use Luminaire Photometrics attached. Luminaire meets efficiency criterion Section 3.2.2 - EMS 1 $CU_{act} = .68 > .55$ for tasks subject to veiling reflections.

1) <u>General Office - 100</u>

$L = 66'$ $W = 40'$ $A_{gross} = 2640'$

$h_{rc} = 5.5$ $RCR = \frac{5(5.5)(66 + 40)}{66 \times 40} = 1.1$ $CU = .68$

T1 - 5 tasks at 100 fc

$A1 = \text{Task Area} = 5 \times 50 \text{ ft}^2 = 250 \text{ ft}^2$

T2 - 16 tasks at 70 fc

$A2 = \text{Task Area} = 16 \times 50 = 800 \text{ ft}^2$

T3 - 4 tasks at 30 fc

$A3 = \text{Task Area} = 4 \times 50 = 200 \text{ ft}^2$

$A_T = \text{Total Task Area} = 250 + 800 + 200 = 1250 \text{ ft}^2$

$$\text{Watts} = \frac{FC \times A}{\text{Lms/watt} \times CU_{act} \times .70}$$

$$\text{Watts(A1)} = \frac{100 \times 250}{40 \times .68 \times .70} = 1313 \text{ watts}$$

$$\text{Watts(A2)} = \frac{70 \times 800}{40 \times .68 \times .70} = 2941 \text{ watts}$$

$$\text{Watts(A3)} = \frac{30 \times 200}{40 \times .68 \times .70} = 315 \text{ watts}$$

General Lighting Level

$$FC_g = \frac{1}{3}\left[\frac{(FC1 \times A1) + (FC2 \times A2) + FC3 \times A3)}{A1 + A2 + A3}\right]$$

$$FC_g = \frac{1}{3}\left[\frac{(100 \times 250) + (70 \times 800) + (30 \times 200)}{1250}\right]$$

$$FC_g = 23.2 \text{ fc}$$

$A_T < A_{gross}$ $\therefore$ Ag = Area General = 2640 - 1250

Ag = 1390 ft^2

$$\text{Watts(Ag)} = \frac{23.2 \times 1390}{40 \times .68 \times .70} = 1694 \text{ watts}$$

Total Watts = 1313 + 2941 + 315 + 1694 = <u>6263 watts</u>

2) <u>Accounting - 102</u>

L = 45' W = 30' A_{gross} = 1350 ft^2

$$h_{rc} = 5.5 \quad RCR = \frac{5(5.5)(45 + 30)}{45 \times 30} = 1.5 \quad CU = .65$$

T1 - 10 tasks at 150 fc

A1 = 10 x 50 = 500 ft^2

T2 - 5 tasks at 70 fc

A2 = 5 x 50 = 250 ft^2

A_T = 500 + 250 = 750 ft^2

$$\text{Watts(A1)} = \frac{150 \times 500}{40 \times .65 \times .70} = 4121 \text{ watts}$$

$$\text{Watts(A2)} = \frac{70 \times 250}{40 \times .65 \times .70} = 962 \text{ watts}$$

General Lighting

$$FC_g = \frac{1}{3}\left[\frac{(150 \times 500) + (70 \times 250)}{500 + 250}\right] = 41.1 \text{ fc}$$

$$A_T < A_{gross} \quad \therefore \text{Ag} = 1350 - 750 = 600 \text{ ft}^2$$

$$\text{Watts(Ag)} = \frac{41.1 \times 600}{40 \times .65 \times .70} = 1355 \text{ watts}$$

Total Watts = 4121 + 962 + 1355 = 6438 watts

3) <u>Private Office - 103</u>

$L = 30'$ $W = 21'$ $A_{gross} = 630 \text{ ft}^2$

$$h_{rc} = 5.5 \quad RCR = \frac{5(5.5)(30 + 21)}{30 \times 21} = 2.2 \quad CU = .61$$

T1 - 2 tasks at 70 fc

$A1 = 2 \times 50 = 100 \text{ ft}^2$

$$\text{Watts(A1)} = \frac{70 \times 100}{40 \times .61 \times .70} = 410 \text{ watts}$$

General Lighting

$$FC_g = \frac{1}{3}(70) = 23.3 \text{ fc}$$

$$A_T < A_{gross} \quad \therefore \text{Ag} = 630 - 100 = 530 \text{ ft}^2$$

$$\text{Watts(Ag)} = \frac{23.3 \times 530}{40 \times .61 \times .70} = 723 \text{ watts}$$

Total Watts = 410 + 723 = 1133 watts

III. Power Calculation - Computer

The following is a sample of a worksheet for data input and a sample terminal input/output for a program developed by Helms. Information on the program will be published in LD&A in late 1976 or early 1977.

PROJECT NAME Office Complex PROJECT NUMBER 75000

CLIENT XYZ CORP. DATE 1976 BY RNH PAGE 1 OF 1

ROOM NUMBER (I3)	WIDTH	LENGTH	HRC	EFFICACY	LUM. SEQ. (I3)	NO. TASKS	TASK 1		TASK 2		TASK 3	
							E	WRK LOC	E	WRK LOC	E	WRK LOC
100	40.	66.	5.5	40.	DB117	3.	100.	5.	70.	16.	30.	4.
101	30.	45.	5.5	40.	DB117	2.	150.	10.	70.	5.		
102	21.	30.	5.5	40.	DB117	1.	70.	2.				

```
PROJECT NAME
? XYZ CORP.
PROJECT NUMBER(I5)
? 75ØØØ
```

Data Input

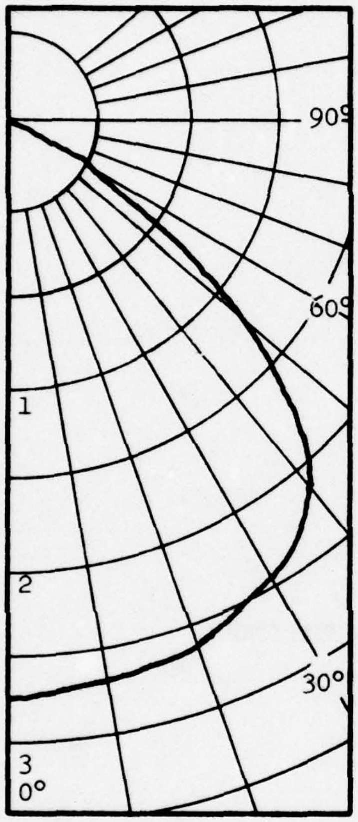
```
 ROOM NUMBER(I3)
? 1ØØ
WIDTH
? 4Ø.
LENGTH
? 66.
HEIGHT OF ROOM CAVITY
? 5.5
EFFICACY
? 4Ø.
 LUMINAIRE SEQ(I5) NO.-RIGHT ADJ.
?    28
NUMBER OF TASKS(I1)
? 3
TASK 1 - E
? 1ØØ.
TASK 1 - WORKER LOCATIONS
? 5.
TASK 2 - E
? 7Ø.
TASK 2 - WORKER LOCATIONS
? 16.
TASK 3 - E
? 3Ø.
TASK 3 - WORKER LOCATIONS
? 4.
```

Computer Output

```
                    ROOM NO.  1ØØ

TOTAL TASK AREA =     125Ø      TOTAL GEN. AREA =     139Ø
     GENERAL FC =       23      NON-CRITICAL FC =       1Ø
            RCR =     1.1Ø                   CU =      .68

          TOTAL ROOM WATTS =      6295

        ROOM WATTS/SQ. FT. =      2.38
```

2' x 4' Troffer

Four F40CW Fluorescent Lamps, Rated 3100 Lumens Each



Candlepower Data
(Average)

Angle	
0	3300
5	3293
15	3210
25	3068
35	2858
45	2338
55	991
65	386
75	255
85	98
90	0

Total Lumens

Zone	Lumens	Percent
0-40	4437	35.8
40-90	3458	27.9
0-90	7895	63.7

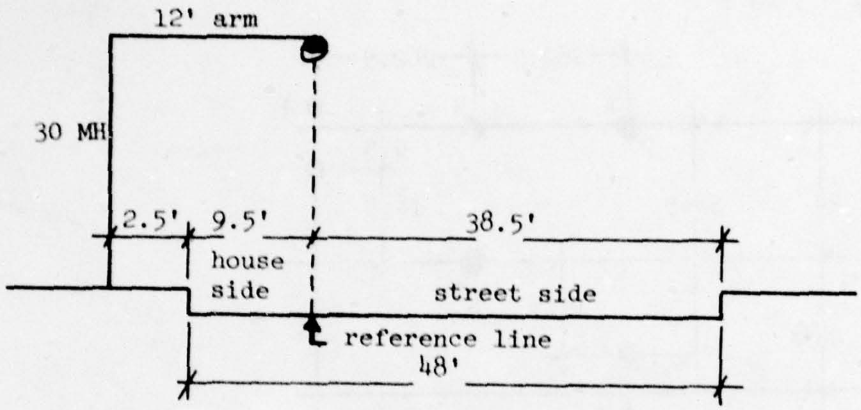
COEFFICIENTS OF UTILIZATION

FLOOR		For ρ_{fc} = 20%								
CEILING		80%			50%			10%		
WALLS		50%	30%	10%	50%	30%	10%	50%	30%	10%
RCR	1	.68	.66	.64	.64	.63	.61	.59	.58	.57
	2	.62	.58	.55	.58	.56	.53	.54	.52	.51
	3	.55	.51	.48	.53	.49	.46	.50	.47	.45
	4	.50	.45	.42	.48	.44	.41	.45	.42	.40
	5	.46	.40	.36	.43	.39	.36	.41	.38	.35
	6	.41	.36	.32	.39	.35	.32	.37	.34	.31
	7	.37	.32	.28	.35	.31	.28	.34	.30	.27
	8	.33	.28	.25	.32	.27	.24	.30	.27	.24
	9	.30	.25	.21	.29	.24	.21	.27	.24	.21
	10	.27	.22	.19	.26	.22	.19	.25	.21	.19

APPENDIX F

ROADWAY LIGHTING CALCULATIONS

Roadway Calculation



E = .5 fc

MF = .70

Act. Lumens = 34000

Use Opposite Spacing

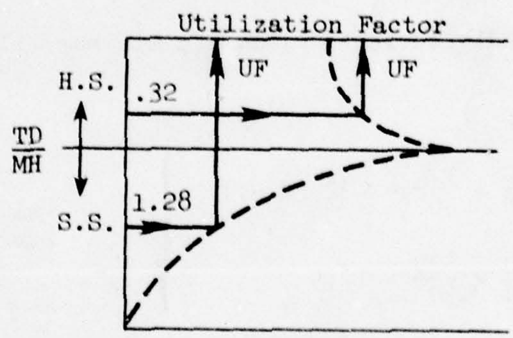
a. $HS = \frac{TD}{MH} = \frac{9.5}{30} = .32$ $\qquad SS = \frac{TD}{MH} = \frac{38.5}{30} = 1.28$

To determine Utilization Factor see Photometric Sheet at the end of this Appendix (superimposed on isofootcandle curve).

$UF_{HS} = .05$

$UF_{SS} = \underline{.48}$

$UF \quad = .53$

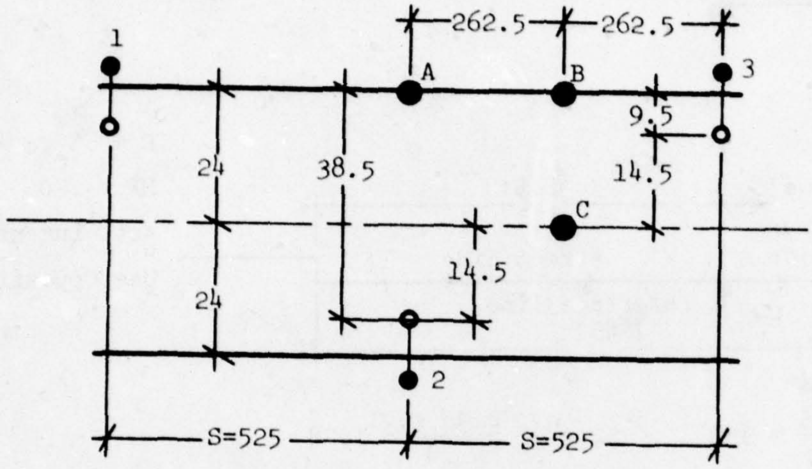


b. $\text{Spacing} = \frac{\text{Lamp LMS x Lamp Factor x UF x MF}}{\text{E x Street Width}}$

$$S = \frac{31500 \times \frac{34000}{31500} \times .53 \times .70}{.5 \times 48.0} = 525.6$$

c. Check Uniformity

Average to Minimum = 3 to 1



Use isofootcandle curve to calculate minimum illumination at points A, B, & C.

Pt.A

From 1 $\frac{TD}{MH} = \frac{9.5}{30} = .32$ (H.S.)

$\frac{LD}{MH} = \frac{525}{30} = 17.5$

Falls of Diag. E = 0
Same From 3

From 2 $\frac{TD}{MH} = \frac{38.5}{30} = 1.28$ (S.S.)

$\frac{LD}{MH} = \frac{0}{30} = 0$

$E = 1.0 \times .70 = .70$ fc

Pt.A

$E_{min} = .70$

$\frac{E_{ave}}{E_{min}} = \frac{.5}{.7} = .71 < 3.0$ o.k.

Pt.B

From 1 $\frac{TD}{MH} = \frac{9.5}{30} = .32$ (H.S.)

$\frac{LD}{MH} = \frac{787.5}{30} = 26.25$ Falls off Diagram $\therefore E = 0$

From 2 $\frac{TD}{MH} = \frac{38.5}{30} = 1.28$ (S.S.)

$\frac{LD}{MH} = \frac{262.5}{30} = 8.75$ Falls off Diagram $\therefore E = 0$

From 3 $\frac{TD}{MH} = \frac{9.5}{30} = .32$ (H.S.)

$\frac{LD}{MH} = \frac{262.5}{30} = 8.75$ Falls off Diagram $\therefore E = 0$

$$\frac{E_{ave}}{E_{min}} = \frac{.5}{0} = \infty \text{ N.G.}$$

d. Spacing to great decrease to 250'

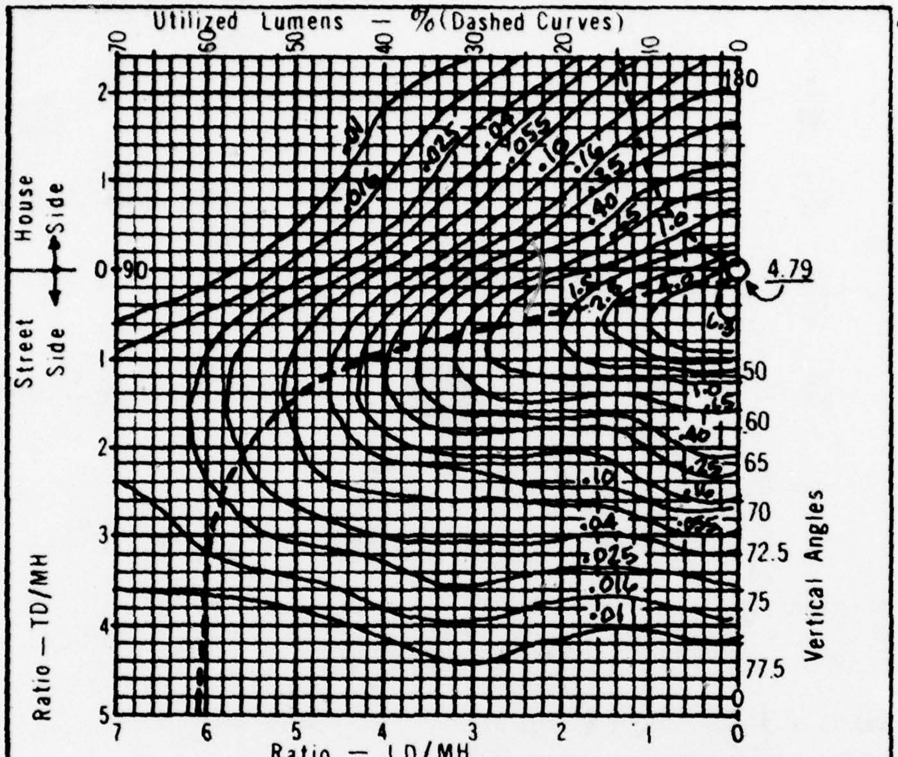
S = 250

$$E_{ave} = \frac{31500 \times \frac{34000}{31500} \times .53 \times .70}{250 \times 48} = 1.05$$

Check E_{min} at each point A, B, C

take ratio

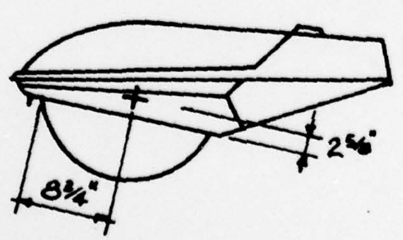
$$\frac{E_{ave}}{E_{min}} = \frac{1.05}{E_{min}} \leq 3.0$$



ISOFOOTCANDLE & UTILIZATION CURVE

Footcandle Data for 30' MH. Utilization Curve No Correction.

MH - FT.	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35
Factor	2.25	2.04	1.86	1.70	1.56	1.44	1.33	1.24	1.15	1.07	1.0	.94	.88	.83	.78	.74



Luminaire Description:

Roadway Unit

TYPE M400 A

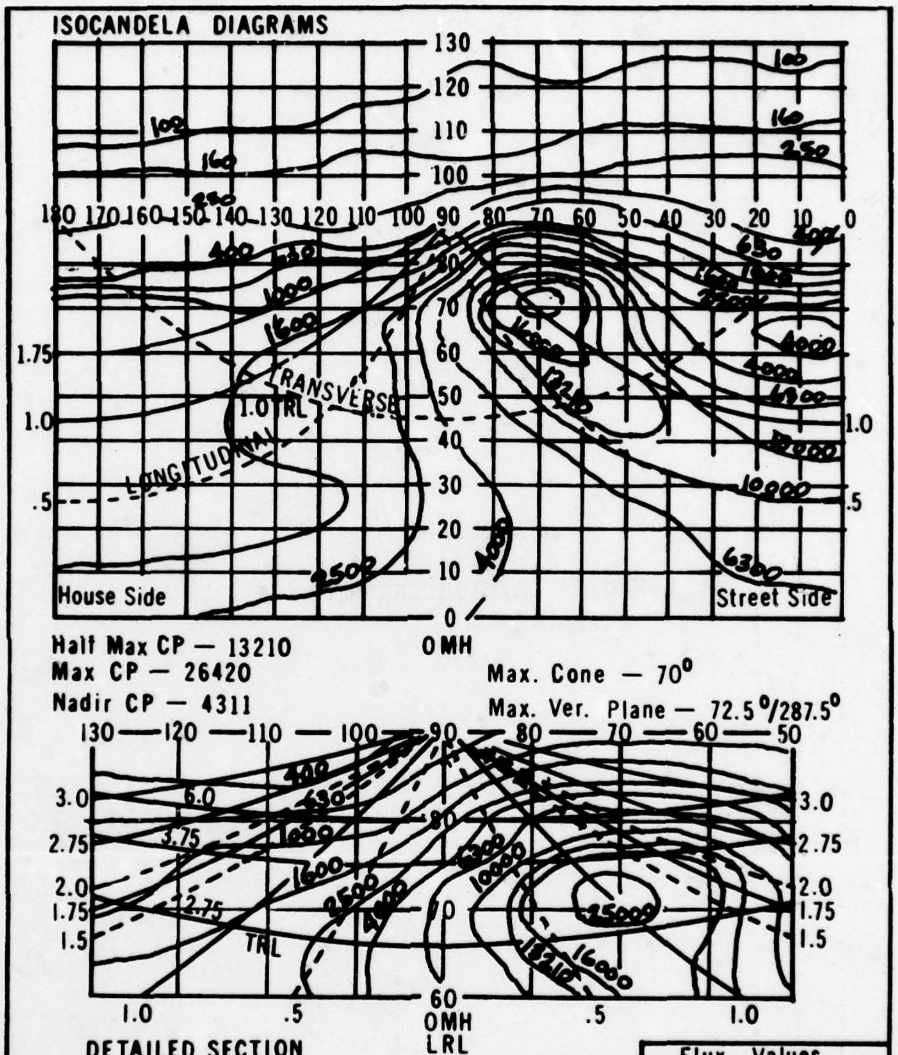
Socket Position 5

Lamp: 400 Watt Metal Halide

Refractor 510

MEDIUM SEMI-CUTOFF TYPE III

No. 30000



Test Lamp Rated at 31500 Lumens

Isocandela, Lumen, & Footcandle Values
Corrected by a Ratio of Act. Lms ÷ 31500.

Flux Values		
	Lms	%
Dw SS	20034	63.6
Up SS	378	1.2
Dw HS	4568	14.5
Up HS	220	.7
Total	25200	80.0

APPENDIX G

LUMEN II DAYLIGHTING STUDY

Daylighting Study of Veiling Reflections

Assumptions:

1. Unilateral Lighting
2. Uniform Diffuse luminance on the window surface
3. Room Reflectances of 80% ceiling, 50% walls, 20% floor
4. No artificial lighting

Variables:

1. Change the size of the window - % Glass area
2. For smaller windows change the location

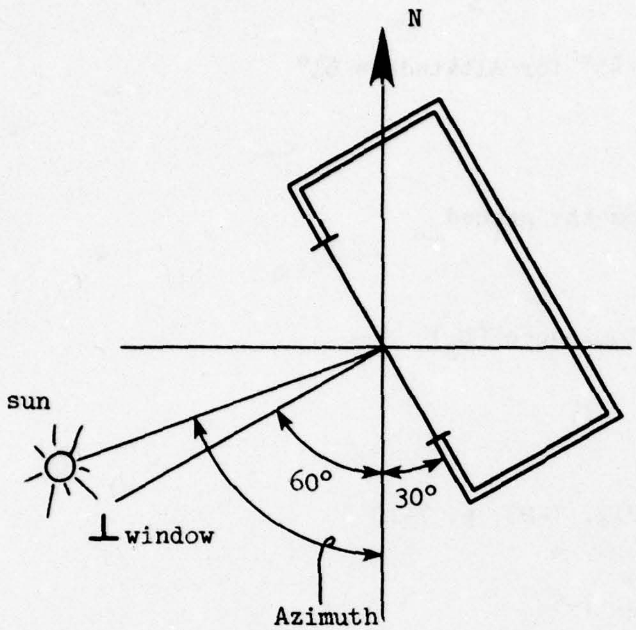
Solution: Using the daylight modification to Lumen II look at the following solutions:

1. Look at the change in raw footcandles as the % glass changes in terms of penetration
2. Look at the change in ESI for each of the compass points of view as the % glass changes
3. Plot ESI and raw footcandles for each combination investigated

Purpose: To develop a feeling for the effect of daylight on visibility in an interior environment. Guidelines for design and placement of windows relative to different classes of tasks may result from this analysis.

APPENDIX H

LONGHAND DAYLIGHTING CALCULATIONS



Room 20' x 20'
10' ceiling height
Window - 12' long x 7' high
w/3' sill height
Latitude 38°N
June 21 2 P.M.

Note: All reference to *IES Lighting Handbook*, 5th Ed.

I. Determine the Illumination Contribution on the Surface of the Window

a. Find Altitude and Azimuth - Fig. 7-7, p. 7-4

Altitude = 61° Azimuth = 70°

b. Find the contribution from the sun - Fig. 7-8, p. 7-5 for June 21 2 P.M. 38°N

$E_{sun_\perp}$ = 8500 fc - on a plane normal to a line from the sun

$E_{sun} = E_\perp \times \cos\theta_1 \times \cos(\theta_2 - \theta_3)$

Solar Altitude, $\theta_1 = 61°$

Solar Azimuth, $\theta_2 = 70°$

Azimuth to Window, $\theta_3 = 60°$

$E_{sun} = 8500 \times \cos 61° \times \cos(70° - 60°)$

$E_{sun} = \underline{4058}$ fc

c. Find the contribution from the sky - Fig. 7-13, p. 7-8

Azimuth from window ⊥ to sun = $\theta_2 - \theta_3$

$Az = 10°$

Interpolate between 0° & 45° for Altitude = 61°

$E_{sky} = \underline{1370}$ fc

d. Find the contribution from the ground

Assume Infinite Area

$E_{ground} = 1/2 \times$ Ground Luminance (L_G)

$L_G = E_h \times \rho_{ground}$

$\rho_{ground} = 6\%$ for grass Fig. 7-23, p. 7-10

$E_h = 7000$ fc Fig. 7-8, p. 7-5

$L_G = 7000 \times .06 = 420$ fL

$E_{ground} = 1/2 \times L_G = 1/2 \times 420 = 210$ fL

d. Total Illumination on Window

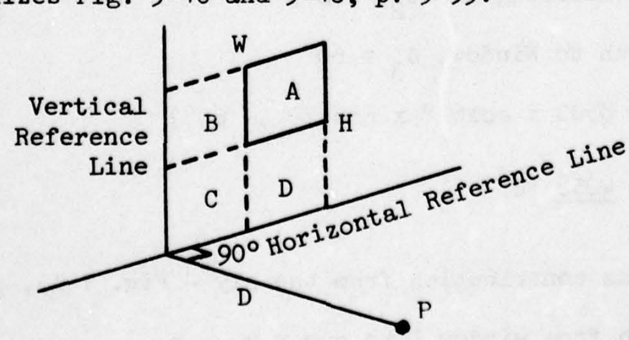
$E_{sun} + E_{sky} + E_{ground}$

$4058 + 1370 + 210 = 5638$

II. Determine the Illumination at a Point in the Room - Point-by-Point Method

a. General Information p. 9-59

Calculation of illumination at a point from a uniform rectangular source utilizes Fig. 9-46 and 9-48, p. 9-59.



To use Fig. 9-48 the following procedure must be used.

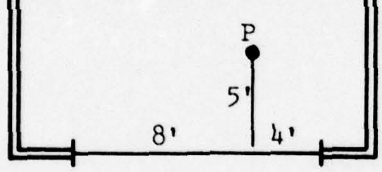
1. Pass a Vertical Plane through point "P" $\perp$ to the wall. The intersection of the plane and the wall forms the "Vertical Reference line."
2. All luminous areas must be in contact with both the Vertical and Horizontal Reference Lines to use Fig. 9-48.
3. To find the Illumination at "P" (E_p) from "A" the following values have to be calculated:

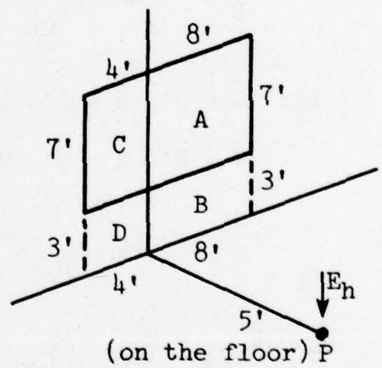
$$E_{P_A} = E_{ABCD} - E_{CD} - E_{BC} + E_C \,*$$

*Note the contribution from "C" was subtracted twice and therefore must be added back once.

b. Point-by-Point - for Example Room

Find the Illumination at point "P" at 5' in from the window. Note that the actual window is AC.





$$E_{P_{AC}} = (E_{AB} - E_B) + (E_{CD} - E_D)$$

From part Ie $E_{TOT} = 5638$ fc

Window Luminance, $L_W = E_{TOT} \times \tau \times LF$

τ - transmission of glass

$\tau = 85\%$ Fig. 7-22, p. 7-9

LF - Light Loss Factor

LF = .90 Fig. 7-31, p. 7-12

$L_W = 5638 \times .85 \times .90 = \underline{4313}$ fL

E_{AB}: $D = 5'$ $H = 10'$ $D/H = .50$

$W = 8'$ $H = 10'$ $W/H = .80$

$\frac{E_h}{L} = .118$ $E_{h_{AB}} = .118 \times 4313 = 508.9$ fc

E_B: $D = 5'$ $H = 3'$ $D/H = 1.67$

$W = 8'$ $H = 3'$ $W/H = 2.67$

$\frac{E_h}{L} = .034$ $E_{h_B} = .034 \times 4313 = 146.6$ fc

E_{CD}: $D = 5'$ $H = 10'$ $D/H = .50$

$W = 4'$ $H = 10'$ $W/H = .40$

$\frac{E_h}{L} = .082$ $E_{h_{CD}} = .082 \times 4313 = 353.7$

E_D: $D = 5'$ $H = 3'$ $D/H = 1.67$

$W = 4'$ $H = 3'$ $W/H = 1.33$

$\frac{E_h}{L} = .024$ $E_{h_D} = .024 \times 4313 = 103.3$

$$E_p = E_{h_{AB}} - E_{h_B} + E_{h_{CD}} - E_{h_D}$$

$$E_p = 508.9 - 146.6 + 353.7 - 103.3$$

$E_p = 612.7$ fc @ 5' from the window

This assumes that the window is a uniform diffuse surface of 4313 fL. The actual illumination will be higher if direct sunlight reaches point "P". This can be determined by making a projection of the window on the floor surface for the specific altitude and azimuth of the sun.

III. Determine the Illumination in the Room - Lumen Method.

a. General

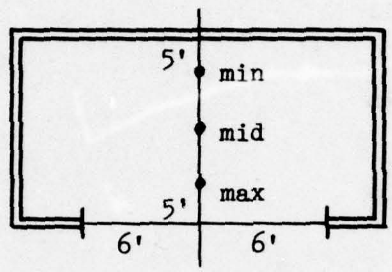
The Lumen Method for sidelight is still under development (p. 9-77).

The available coefficients are for sky and ground contributions only. The method calculates three points on the work plane on a line perpendicular to the centerline of the window.

K_{max} - 5' from the window

K_{mid} - midpoint along the line

K_{min} - 5' from the inner wall



b. Lumen Method for Sidelight.

$E_p = E_i \times A_w \times K_u \times K_m$

E_i - Illumination on the window from sky or ground.

A_w - Gross area of window

K_u - Utilization coefficient

K_m - Light loss coefficient

$E_{i_{sky}} = 1370$ fc (clear sky)

$E_{i_{ground}} = 210$ fc

$A_w = 12' \times 6'$

$A_w = 72'$

$K_m = \tau \times LF$ (Fig. 7-22, p. 7-9 & Fig. 7-31, p. 7-12)

$K_m = .85 \times .90$

$K_m = .77$

Assume the conditions of Fig. 9-77 (A.), p. 9-78. Use wall reflectance = 50% (interpolate between 70% & 30%).

20 x 20 with 10' ceiling

sky: $K_{u_{max}} = .00178$

$K_{u_{mid}} = .00111$

$K_{u_{min}} = .00070$

ground: $K_{u_{max}} = .00128$

$K_{u_{mid}} = .00098$

$K_{u_{min}} = .00069$

Max: $E_{p_{sky}} = E_{i_{sky}} \times A_w \times K_{u_{max}} \times K_m$

$E_{p_{sky}} = 1370 \times 72 \times .00178 \times .77$

$E_{p_{sky}} = 135.2$

$E_{p_{ground}} = E_{i_{ground}} \times A_w \times K_{u_{max}} \times K_m$

$E_{p_{ground}} = 210 \times 72 \times .00128 \times .77$

$E_{p_{ground}} = 14.9$

$E_{max} = E_{p_{sky}} + E_{p_{ground}} = 135.2 + 14.9 = 150.1$

Mid: $E_{p_{sky}} = 1370 \times 72 \times .00111 \times .77 = 84.3$

$E_{p_{ground}} = 210 \times 72 \times .00098 \times .77 = 11.4$

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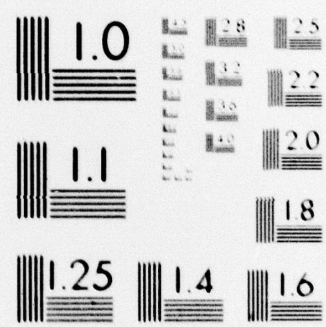

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$E_{mid} = 84.3 + 11.4 = 95.7$

Min: $E_{p_{sky}} = 1370 \times 72 \times .00070 \times .77 = 53.2$

$E_{p_{ground}} = 210 \times 72 \times .00069 \times .77 = 8.0$

$E_{min} = 53.2 + 8.0 = 61.2$

c. Summary

$E_{max} = 150.1$ fc

$E_{mid} = 95.7$ fc

$E_{min} = 61.2$ fc

APPENDIX I

LUMEN II DAYLIGHTING CALCULATIONAL PROCEDURE

In addition to or instead of determining the effect of artificial lighting systems at a rectangular grid of points, Lumen II can calculate the effect of daylight. That is, if the user wishes, the horizontal illuminance or equivalent sphere illuminance produced by daylighting can be added (in the appropriate manner) to any values present due to artificial lighting.

Daylighting calculations are performed using a data based supplied with Lumen II, and user specified information. The daylighting data base consits of sky luminance distributions for various sky conditions and solar positions. User supplied data is used to specify what sky luminance distribution is to be used and how it produces illuminance in the room. This user information includes:

- Desired sky condition
- Day of the year and time of day
- Latitude and orientation of room
- Size and location of windows
- Transmittance of windows
- Size and location of skylights
- Transmittance of skylights

If desired, Lumen II can account for the presence of daylighting controls which are part of the exterior building architecture, such as overhangs, recesses and vertical vanes which are near the windows. User supplied information includes:

- Size and location of overhangs
  - Reflectances of overhangs
- Size and location of vertical vanes
  - Reflectances of vertical vanes

If desired, Lumen II can account for the presence of daylighting controls which are part of either the fenestration or interior architecture, such as shades, blinds, or drapes. User supplied information includes

- Size and location of

  Shades
  Blinds
  Drapes

- Transmittance and reflectances

The presence of separate building structures external to the room affects the view of the sky that any point in the room will have. These include shadowing and luminance substitution due to reflection off of an adjacent building with diffuse or specular reflectance. These affects can be taken into account using user specified information which includes:

- Size, location, and orientation of adjacent buildings

- Type of reflectances

- Values of reflectances

Adequate accuracy can be expected because assumptions are not made which would permit the use of uniform sky luminance or equivalent sky luminance. The effect of the variable sky luminance distribution is taken into full account.